GROUND WATER MONITORING

A GUIDE TO MONITORING FOR AGRICULTURAL NONPOINT SOURCE POLLUTION PROJECTS

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January 1996

ACKNOWLEDGEMENTS

The efforts of several individuals made this document possible. The authors acknowledge Mike Kuck for his strong arm of support and Diane Clayton for protecting us from our own schedule. A special thank you is extended to Dr. John Clausen, Steve Dressing, Don Meals, Dennis Erinakes, and Cindy Steele for their technical reviews; this document benefitted from their expertise. And finally, the assistance from Nancy Stuefen in the final preparation of the text is greatly appreciated.

Published By:

United States Department of Agriculture
Farm Service Agency
200 Fourth Street, Southwest
Huron, South Dakota
605-352-1160

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION AND PURPOSE

Interest in nonpoint source pollution control was renewed with the 1987 Clean Water Act Amendments. These amendments provided for strengthened state Nonpoint Source Pollution Management programs through funding under Section 319 of the Act. The renewed interest brought with it questions and problems regarding the methods and extent of the measurements needed to document nonpoint source pollution control success. This was particularly true for measuring the success of practices to reduce adverse ground water impacts due to nonpoint source pollution.

Section 319 Nonpoint Source Pollution Control projects of the 1990's and beyond can benefit from the experiences and the lessons learned from the 10-year Rural Clean Water Program (RCWP). The RCWP was a United States Department of Agriculture sponsored nonpoint source pollution control program. The objectives of the program were to cost-effectively improve water quality in selected agricultural watersheds and assess the water quality benefits from the application of best management practices. Best management practices were defined as practices or structures designed to reduce the quantities of pollutants while maintaining farm profitability. Twenty-one RCWP projects across the nation participated in the experimental RCWP during the 1980's. The projects consisted of applying best management practices to a locally defined critical land area and measuring the success of the practices by monitoring surface water, vadose zone, and ground water quality.

Annual and final project reports, annual workshops, and project evaluations helped to document the processes and results of the RCWP. The RCWP was conducted in a way that allowed for a substantial uniformity in reporting and the exchange of information regarding

what worked and what did not work. This document refers to several RCWP-based publications that should be helpful to new and ongoing nonpoint source pollution control projects.

South Dakota implemented one of the two RCWP Comprehensive Monitoring and Evaluation projects which focused on the impacts best management practices had on ground water quality. The Oakwood Lakes-Poinsett project was also one of the three RCWP projects with the objective of controlling nonpoint source pollution of the ground water. As in many RCWP projects, South Dakota had to tailor the monitoring processes and methods to meet its specific objectives in the project area. Methods to evaluate the cause and effect relationship between the application of best management practices and ground water quality were also developed.

The Oakwood Lakes-Poinsett RCWP project generated new and useful information regarding processes and methods for monitoring all aspects of the hydrologic cycle, including ground water in nonpoint source impacted areas. **The purpose of this document is to provide a readable, "how to" handbook for designing and operating a ground water monitoring network for nonpoint source pollution control projects based on the South Dakota experience.** Project processes from problem identification through water quality data evaluation are presented. The major emphasis of the document is monitoring the impacts of nonpoint source pollution to ground water, the vadose zone, and surface water via the ground water connection.

This is not an all encompassing guidebook, but it documents what worked and what did not work in the Oakwood Lakes-Poinsett RCWP project and the other RCWP projects. It provides some alternatives to guidance documents for spill assessment and clean-up sites. Techniques for monitoring the surface water/ground water interaction, the vadose zone, and the zone of saturation that are more applicable to agricultural situations are presented. Many

techniques described are unique and innovative; others are standard techniques used in the field. Some techniques worked, others did not.

The information provided in this document is geared mainly toward the hydrologic systems and geologic regimes of the glaciated, upper Midwestern region of the United States. However, the lessons learned in this project can be used in designing monitoring projects in all parts of the country. The Oakwood Lakes-Poinsett project area is dominated by glacial features including prairie lakes and wetlands, moraines (till) and outwash aquifers (sand and gravel). **This does not preclude users in other areas from gaining useful information on monitoring nonpoint source pollution control projects.** The information provided on a **project process** is also very useful and is recommended as required reading by those entities charged with developing and implementing projects. **Project planners/developers, project managers, project monitoring personnel, conservation districts, lake associations, farm groups, environmental consultants, and others can benefit from using this document.**

The reader is referred to the final RCWP evaluation by the National Water Quality Group at North Carolina State University. The document includes a description of the RCWP and of each RCWP project, and a complete list of available RCWP documents. The evaluation is entitled "Evaluation of the Experimental Rural Clean Water Program." It is an Environmental Protection Agency document EPA-841-R-93-005, May 1993. The reader is also referred to the list of references for subsurface monitoring techniques in this document.

RURAL CLEAN WATER PROGRAM BACKGROUND

PROGRAM OVERVIEW

The RCWP was a federally sponsored program designed to control agricultural nonpoint source pollution in rural watersheds with the goal of improving water quality. Initiated in 1980, the RCWP was established as a 10 to 15 year experiment offering cost-sharing and technical assistance as incentives for voluntary implementation of best management practices.

The objectives of the RCWP were to:

- Achieve improved water quality in the approved project area in the most cost-effective manner possible while assuring adequate supplies of food, fiber, and a quality environment;

- Assist agricultural land owners and operators in reducing agricultural nonpoint source water pollutants and in improving water quality in rural areas to meet water quality standards or water quality goals; and

- Develop and test programs, policies, and procedures for the control of agricultural nonpoint source pollution.

With a total appropriation of $64 million, the RCWP funded 21 watershed projects throughout the United States. These projects represented a wide range of pollution problems and impaired water uses. The RCWP projects were selected from state lists of priority watersheds developed during the Section 208 planning under the 1972 Clean Water Act. Projects were located in Alabama, Delaware, Florida, Idaho, Illinois, Iowa, Kansas, Louisiana, Maryland,

Massachusetts, Michigan, Minnesota, Nebraska, Oregon, Pennsylvania, South Dakota, Tennessee/Kentucky, Utah, Vermont, Virginia, and Wisconsin.

Each project involved both land treatment and water quality monitoring. Landowners were contracted to implement best management practices, with the length of the contract depending on the practice being implemented. Contracts were typically a minimum of three years (e.g., conservation tillage) and a maximum of ten years (e.g., terraces, animal waste management systems) in length. Most RCWP project contracts began in 1980-81 and ended in 1986, with project results evaluated and presented in 1991. The RCWP ended in 1992; however, a few individual projects were extended until 1995. While water quality monitoring was done in all 21 projects, five of the RCWP projects (Idaho, Illinois, Pennsylvania, South Dakota, and Vermont) were selected to receive additional funding for comprehensive monitoring and evaluation.

The RCWP was administered by the U.S. Department of Agriculture's Agricultural Stabilization and Conservation Service (now known as the Consolidated Farm Service Agency). Based on the principle of interagency cooperation and the existing federal/state/local partnership, the RCWP was also assisted by other federal agencies, including the Soil Conservation Service (now known as the Natural Resource Conservation Service), Environmental Protection Agency, Extension Service (now known as the Cooperative State Research Education and Extension Service), Forest Service, Agricultural Research Service, Economic Research Service, and Farmers Home Administration (now known as the Rural Economic Community Development), and many state and local agencies.

Both direct water quality benefits and a wealth of experience in agricultural nonpoint source pollution control resulted from the RCWP. Results and lessons learned from RCWP projects are an important source of information for other federal and state nonpoint source pollution

control programs. The program has also helped to define research needs and increase public awareness of many important water quality problems.

Each of the 21 RCWP watershed projects prepared a 10-year report. The 10-year reports described the watershed project, the monitoring conducted, the results as of 1991, and the recommendations from the project. These 10-year reports, other project data, and on-site project evaluations provided the basis for a final summary and evaluation of the entire RCWP, prepared by the National Water Quality Evaluation Project at North Carolina State University.

SOUTH DAKOTA RCWP PROJECT OVERVIEW

The Oakwood Lakes-Poinsett project was located in the glacial lakes region of east-central South Dakota. The project area was over 106,000 acres in size with 79,450 acres of cropland identified as the project's critical area needing treatment. The critical project area was defined as cropland that may overlie the aquifer (the full extent of the aquifer had not been mapped). Row crop agriculture was the major land use with corn, soybeans, alfalfa and small grains identified as the major crops produced. The water quality problems identified within the Oakwood Lakes-Poinsett project area were elevated nitrate levels in certain areas of the Big Sioux aquifer and hypereutrophic lakes caused by the nutrient loading from the watershed.

The State Coordinating Committee, chaired by the Agricultural Stabilization and Conservation Service State Executive Director, was the project's decision-making body. The State Coordinating Committee acted on the recommendations of the Local Coordinating Committee. The land treatment team consisted of: Conservation District and County Committee staff, Soil Conservation Service staff, and a technical planner. The Comprehensive Monitoring and Evaluation (CM&E) team consisted of staff from the Department of Environment and Natural Resources (DENR) and South Dakota State University (SDSU). The land treatment and

CM&E teams advised the Local Coordinating Committee and State Coordinating Committee. The land treatment team and the CM&E team were linked by the Soil Conservation Service project coordinator.

The land treatment goal of the project was to use best management practices to reduce the amount of nitrogen and pesticides entering ground water, and to reduce nitrogen, phosphorus, and sediment entering surface water. The CM&E goal of the project was to monitor the effects and evaluate the impacts of best management practices to ground water and surface water.

A study conducted by the Economic Research Service evaluated economic and water quality conditions before RCWP, in the future without RCWP, and in the future with RCWP. The study predicted that improved fertilizer management represented the most cost-effective strategy for meeting nutrient loading goals. An evaluation of the off-site impacts of RCWP predicted a 20% increase in the recreational use of the Oakwood Lakes if the algal blooms in the lakes were reduced. This would result in a return of $117 per eligible acre compared to an investment of $33 cost share per acre and technical assistance.

Four best management practices (conservation tillage, fertilizer management, pesticide management and animal waste management) were emphasized to accomplish the land treatment goal. The critical project area was divided into three priority areas. The areas were determined by combining three levels of sediment delivery to lakes and four aquifer vulnerability categories. Priority Area 1 consisted of 59,500 acres with direct sediment delivery to lakes and the shallowest depths to the aquifer. Priority Areas 2 and 3 consisted of acres with indirect sediment delivery and thicker materials over the aquifer.

RCWP contracts to implement best management practices were established on 48,088 acres, covering 60% of the critical project area, or 81% of the Priority Area 1. Cost-share assistance

was provided by RCWP funds administered by the Agricultural Stabilization and Conservation Service. A rate of 75 percent of total costs, up to a maximum of $50,000 federal contribution per operator was available. The total cost-share assistance provided to producer participants in South Dakota was $740,337.

The CM&E project was designed to describe the cause and effect relationship between agricultural management practices and the quality of both the ground water and surface water resources of the study area. The approach for the monitoring was to study the soil profile and ground water at small field sites, the surface water in the Oakwood Lakes system, and the water and nutrient movement through the unsaturated zone at a plotted experimental site.

For this project to be successful, all aspects of the hydrologic system had to be monitored, because each component of the cycle influenced another component. The surface water was hydraulically connected to the shallow aquifer, which was interrelated to the vadose zone. These components were influenced by the agricultural practices on the land surface.

For both lakes and aquifers, direct monitoring of the resource targeted for protection or improvement was important. Mechanisms influencing the resources were also monitored. The ground water monitoring was conducted at six farmed fields and one unfarmed site with the use of nested monitoring wells. The Oakwood Lakes system monitoring included direct measurement of both surface water and ground water inputs and in-lake water quality. Unique, event-based techniques for monitoring water and chemical movement in the vadose zone were used. The frequency of monitoring was also very important to the success of the monitoring program.

Ground water monitoring results from the South Dakota RCWP indicated significantly higher concentrations of nitrate in ground water at the farmed sites than the unfarmed sites. Fertilizer application rates, infiltration events, and denitrification were the dominant factors

controlling nitrate (as nitrogen) concentrations in the ground water. Concentrations of nitrate greater than five (5) milligrams per liter as nitrogen were found only in water samples collected from depths less than 20 feet below the water table. **Concentrated leaching of pesticides was not detected in the ground water at sites where the pesticides were applied according to label instructions.**

Vadose zone monitoring showed that the use of no-till on cropped research plots increased soil infiltration rates. The amount of water and nitrates reaching the ground water was greater for the no-till treatment than for the moldboard plow treatment. The most significant flow pathways in the vadose zone were pores greater than one millimeter in diameter, although the pores of this size comprised less than 40% of the total pore area.

The surface water/ground water interaction monitoring resulted in the development of water and nutrient budgets for the Oakwood Lakes system. In some years, 50% of the water input to the lake system was ground water. Ground water contributed 5-11% of phosphorus and 12-30% of total nitrogen in the lakes' nutrient budget.

NONPOINT SOURCE PROJECT ELEMENTS

INTRODUCTION

There are several elements that can be listed while developing and carrying out a nonpoint source pollution project. In addition, each element may consist of several steps or components. Each project may differ in what is considered "key" or "essential" elements, and authors of guidance documents for conducting a project may choose to identify various project elements. Following are descriptions of the project elements that were key to the success of the RCWP projects, specifically in the South Dakota Oakwood Lakes-Poinsett Project. These elements are:

Problem Identification
Project Development
Institutional Arrangements
Water Quality Monitoring
Quality Assurance/Quality Control
Land Use Monitoring
Project Evaluation
Reporting/Information Dissemination

Each element consists of several components that make it work and add to the success of the project. The reader is encouraged to consider these elements as essential to projects intending to document improved water quality achieved by adopting best management practices.

PROBLEM IDENTIFICATION

Purpose

One key element to project success often discussed in the final RCWP project reports and RCWP program evaluation, is accurate **problem identification**. Problem identification is the foundation from which the project objectives are established. Inadequate, incomplete, or inaccurate definition of the water quality problem and its cause can lead to: 1) objectives that cannot be met, 2) a focus on the wrong or lower priority pollution source(s), and 3) ineffective expenditures of project funds. **The RCWP illustrated that correctly identifying and documenting a water quality problem is one of the most critical steps in controlling agricultural nonpoint source pollution (Osmond et al., 1995).**

How to Identify Water Quality Problems

Problem identification is the first step in the nonpoint source project process, but it can be refined as the project is developed and after monitoring data become available. Problem identification usually begins with a complaint about or realization of an impairment of a water body. Local concerns about a water quality problem often stimulate government agency action to identify and address water quality problems.

Water quality problems may be readily identified in a surface water body with easily observed evidence of algal blooms, poor fishing, turbid water, or fish kills. This may even be readily identified in ground water produced in a karst area where visible pollutants enter the subsurface and travel through large fractures to a well. A water quality impairment in an unconsolidated aquifer may go undetected until a laboratory test is done. Other impairments such as high nitrate concentrations may be detected only after a health problem such as methemoglobinemia has been identified. Some local people may not recognize or accept the

fact that a water quality problem exists. This can hinder any progress in developing a project to address the problem.

Existing data may be adequate to initially identify the water quality problem, but additional water quality and land use monitoring may be necessary to further characterize the problem. Water quality monitoring can be used to identify specific pollutants causing the problem and to verify the source of these pollutants.

Once the water quality problem is identified, a clear problem statement is needed to provide a basis for the project strategy. The problem statement links a pollutant to a water resource and helps to focus project participants. The reader is cautioned to address the <u>source</u> of the problem, not the symptom of the problem (USDA-NRCS, in press). For example, a problem statement identifying algal blooms in a lake would not be appropriate; instead, a nutrient source such as a poorly managed feedlot on the edge of the lake might be the pollution problem causing algal blooms in the lake.

The problem statement should identify the problem (what), which water body is threatened or impaired (where), the cause of the problem (why), and the source of the cause (what/where/how).

> **An example of a problem statement from the Oakwood Lakes-Poinsett RCWP project is**: High nitrate concentrations (what) in portions of the Big Sioux aquifer (where) threatened its use as a drinking water supply (why) because of improperly managed animal waste and fertilizer use over the aquifer (what/where).

The problem statement is used as a guide in the selection and location of best management practices and for building community consensus for the project.

Lessons Learned from RCWP

- **Problem definition is dependent upon pre-project data collected from the project area.**

- **Problem definition may be refined based on new information obtained from water quality monitoring or data evaluation.**

- **The problem must be on a scale that can be addressed by the project.**

- **All sources of pollution must be identified in the problem identification phase so all sources can be prioritized for treatment.**

- **Water quality problems, pollutants, and impacts on designated uses should be clearly defined and documented.**

- **A consensus among local people regarding the presence of a water quality problem is needed for project development.**

Case Studies from RCWP

Minnesota - The Garvin Brook RCWP project illustrated the importance of focusing on water quality problems that are as important to the project area landowners and operators as they are to the land treatment and water quality agencies. The initial water quality problem identified in the Garvin Brook RCWP project was impaired trout fishing in a stretch of Garvin Brook due to sedimentation and habitat destruction. Although this problem was real, the farmers in the project area did not appreciate the benefits of addressing this problem. The project focus shifted to addressing the problem of high nitrate concentrations and pesticides in the aquifers

supplying water to domestic wells in the project area. Farmer participation in the application of best management practices to address this problem increased as a result. The project was successful in meeting the objectives set to address the ground water problems (Wall et al., 1989).

South Dakota - The Oakwood Lakes-Poinsett RCWP project illustrated the need to identify and set priorities for all potential sources of pollution. Fertilizer management was emphasized initially in the project to address excess nutrients in the tributaries to Oakwood Lakes and high nitrate concentrations in the aquifer. As the project progressed, monitoring data showed animal waste from small feedlots in the project area was a major contributor of nutrient inputs to the surface water. Managing animal waste in the Oakwood Lakes watershed improved the quality of the water delivered to the lakes (Goodman et al., 1991).

Idaho - The Rock Creek RCWP project also illustrated the need to identify and set priorities for all potential sources of pollution. Impairment of Rock Creek caused by sediments and nutrients from irrigation return flows and animal waste was the identified problem in the project. The Rock Creek project was very successful in the implementation of best management practices to address the irrigation return flows and animal waste problems. Monitoring results showed improvements in the water quality of Rock Creek. Stream bank erosion, however, continued to be the major contributor of sediment to Rock Creek and had to be addressed to achieve further water quality improvements (Maret et al., 1991).

PROJECT DEVELOPMENT

Purpose

Once the water quality problem has been identified, the next element in the process is project development. It is beneficial to establish a committee to develop the project and draft a proposal and workplan. This committee may be small at first but may grow as the process evolves.

How to Develop an Effective Project

The **process of nonpoint source project development** should include the following main steps:

- Form a project development committee
- Establish project objectives
- Write a proposal
- Develop a budget
- Submit proposal for funding
- Develop a workplan

Form a Project Development Committee

Once the water quality problem has been identified, a leader is needed to facilitate project development. Often, the leader in project development is a local, state, or federal agency person or a recognized expert in nonpoint source pollution control. This person can provide valuable expertise in the project development process. The leader can also mediate between those at the source of the problem and those affected by the problem. As an example, a feedlot operator may not perceive that the daily activities at the feedlot contribute to a

nonpoint source problem. However, rural water system users may be affected by that feedlot operation. Both interests should be represented on the project development committee.

Representatives from local agencies or organizations that are potential project sponsors should also be included on the committee. The necessary committee participants are:

- Landowners/producers in the project area
- Local natural resource conservation board director
- State and/or federal water resource professionals
- Adversely impacted water users

Other committee members that may perform key functions or provide useful information may include:

- University water resource research professionals (if located near the project)
- Regional water conservation/development district directors/manager
- Regional Cooperative Extension water quality specialists
- District Conservationists
- County commissioners
- Lake association board members
- Farm group leaders

The final composition of the project development committee will depend on the needs of the project and will vary between projects. Limiting the membership of a project development committee is not encouraged, but a large committee may hinder the development process. The committee size must be balanced with the scope of the project.

The proposed project may be rejected at this stage because some committee members may not accept the project idea. Committee members who are open-minded, have a team-approach, are enthusiastic about the project, and are interested in maintaining or improving water quality will promote the acceptance of the project. Unanimous approval from all committee members is not necessary, but a majority should accept the idea to solve the nonpoint source problem. **Good background water quality information can be the foundation for committee members to develop a consensus on the project.**

Establish Project Objectives

The next step in project development is establishing the project objectives. The objectives should be consistent with the identified water quality problem. There may be many tasks planned to meet the project objectives; the sum of completing these tasks should be the total attainment of the project objectives.

Each objective should specify the desired result of the project and what must be done to achieve the objective. The USDA-NRCS (in press) describes a useful syntax for writing an objective:

> **Infinitive verb + object word or phrase + constraints**
>
> An infinitive is a verb form that is usually preceded by the word "to."
>
> Some examples are:
>
> > **To reduce...**
> >
> > **To implement...**
> >
> > **To assess...**
>
> The second component of an objective statement is the object. The object receives the action of the verb and answers the question, "What?":
>
> > To reduce **the nitrogen loadings by 50%.**

Constraints limit the objective statement to specified areas. The objective becomes constrained from the whole world of opportunities or alternatives:

To reduce + the nitrogen loadings by 50% + **to the Big Sioux aquifer.**

Most projects will have an overall objective with several sub objectives. These may include objectives for various components of the project. For example, there may be information and education objectives, economic evaluation objectives, land treatment implementation objectives, and water quality monitoring objectives. The number of sub objectives will depend upon the scale and scope of the individual project.

At this point of the project development, the planning for water quality monitoring should begin. More discussion on developing monitoring objectives and a monitoring plan is found in the "Water Quality Monitoring" and "Land Use Monitoring" sections of this document.

The scale and scope of the project needs to be addressed as objectives are formulated. The project development committee should choose the scale and scope of the project based on what can be accomplished. Consideration should be given to the time frame, potential funding, socioeconomic acceptance, and other factors that may affect the scale and scope of the project. **The most common error in deciding the scale of a project is to make the project too large.**

Another consideration in the development of project objectives is the approach that will be used to accomplish the objectives. The approach answers the question of how the objectives will be met and decides the tasks necessary to complete a project. As an example, the approach to reduce nitrogen loading to an aquifer may be one of the following: 1) through regulation of potential pollution sources, 2) voluntary implementation of best management practices, or 3) remediation of large areas of contaminated soils. The approach chosen will determine the roles of various groups and agencies in the project.

Write a Proposal

One or two people on the project development committee who have had experience in proposal writing should be responsible for the final assembly of a proposal. The content of the proposal, however, should be based on the consensus of the committee. Although only a few committee members may be involved in writing the proposal, the entire committee should be involved in the review and approval of the final proposal. As the proposal is developed, drafts of the document should be prepared and delivered to each committee member before the meetings. This stimulates focused discussion and may prevent the revisiting of previous points of discussion. For those who are responsible for assembling the proposal, this format provides for participation by the full committee.

A suggested format for a proposal is:

- **Abstract:** concise summary of the proposal less than a page in length.
- **Introduction:** problem identification, objectives, project scale, and length of time.
- **Background information and literature review:** what information is available and what has been done?
- **Materials and methods:** how will objectives be achieved? What, where, and when to monitor?
- **Project evaluation:** what will be done with the data collected, and how will they be analyzed?
- **Budget**

Develop a Budget

One important step in writing a project proposal is preparing a budget. The budget needs to reflect the identified water quality problem, the project objectives, and the scope of the project. A detailed budget for each year for the life of the project should be completed. At this point, a reevaluation of the objectives and scale of the project may be needed if the budget is unrealistic.

The budget should include a breakdown of funding sources, including the available matching funds. The matching funds in in-kind service should also be included. All project tasks need to be included in the budget. Costs for labor, equipment, and operating and maintenance should also be included in the budget. A personal computer spreadsheet with cell formulas helps in developing and updating a detailed budget.

Submit the Proposal for Funding

Determination of the **potential** for funds should be done early in the process. The focus of the funding agency's programs and the history of funding projects should be researched. Direct contact to the funding agency coordinator may provide information about the program focus. **Success in obtaining funds for nonpoint source projects may depend significantly on the national and state trends in water quality issues.**

Develop a Workplan

The final stage of the project development process is developing the workplan. The workplan should include a timeline of activities over the life of the project. The workplan should list each objective and the tasks needed to complete that objective. A table of each task, the agency or person responsible for each task, the time line, and completion date should be

included in the workplan. The workplan should include the water quality monitoring plan and other plans to complete tasks in support of the project objectives.

The schedule for the workplan should be realistic. Tasks to be completed before other tasks can begin should be identified to prevent project delays. The workplan may need to be reevaluated as the project progresses. It is important that deadlines and projected completion of activities be held as close to schedule as possible to prevent compounding delays.

Lessons Learned from RCWP

- **The conceptual idea for a project must be well documented with background information that an impaired water resource exists.** This fosters increased acceptance among project development committee members.

- **Patience is necessary in the project development stage to allow time for consensus among project development committee members on how to solve the nonpoint source pollution problem.**

- **Some members of the project development committee should continue to be involved as implementation of the project begins.**

- **The water quality problem, the value of the water resources, and the magnitude of the pollution source must be critically identified to develop attainable objectives.**

- **The scale of the project should be limited to ensure the objectives can be accomplished.**

Case Study from RCWP

South Dakota - The Oakwood Lakes-Poinsett RCWP project application was prepared by local and state coordinating committees. The original proposal was to assess the effectiveness of best management practices on lakes in the project area. The focus of the project changed, however, before the workplan was submitted. With a change in emphasis to protect ground water resources, the Local Coordinating Committee redirected the focus of the water quality contracts to include conservation tillage, fertilizer management and pesticide management. The project area encompassed portions of three counties which made organization of the Local Coordinating Committee a challenge. A cooperative attitude between participants made development of a successful project possible (Goodman et al., 1991).

INSTITUTIONAL ARRANGEMENTS

Purpose

Once a project is funded, institutional arrangements encompassing project planning, management, and administration need to be formalized. Effective cooperation and coordination of agency personnel, landowners, community leaders, and others involved in the project ensure high landowner participation in the project, which is a key to a project's success (Gale et al., 1995). Within the institutional arrangements of a project, each agency and project participant should understand each other's responsibilities (Stanley, 1992).

How to Develop Effective Institutional Arrangements

The agencies, organizations, community, and landowner representatives involved in the project need to be organized into some type of coordinating or advisory committees and implementation teams. The project development committee may become the source of core

members for the coordinating committee. This can occur at the local, state, or national level, depending on the funding and administrative mechanisms for the project.

Local, state and national coordinating committees were used successfully in the RCWP projects. Some RCWP projects complemented the coordinating committees with implementation teams. These teams focused on specific tasks such as water quality monitoring, land treatment, report management, information dissemination, and economic analysis. The teams reported their progress, requested additional resources, and obtained their direction from the coordinating committees. Figure 1 illustrates the organizational structure of the South Dakota RCWP project and the relationship of the project's committees and teams.

The coordinating committees oversee the implementation of the project. A local coordinating committee can oversee land treatment implementation in the project area and can assure public involvement in the project. State coordinating committees coordinate the general direction of an individual project. National committees can provide overall program guidance, ensuring a certain level of uniformity among projects. As the committees review project status, workplans can be modified as needed. This requires the committees to be flexible and willing to change things that are not working in the project. Funding and administrative mechanisms can also be developed and carried out by the committees.

A project manager or leader should be hired or designated from a participating agency to coordinate the project and assess its progress (Gale et al., 1993). The project manager does not necessarily chair the committees or teams, but acts as a coordinator and liaison between various agencies, committees, and teams (Kuck and Goodman, 1992). Lines of communication and coordination between teams and committees are critical. The project manager should have an understanding of all aspects of the project and should develop a close

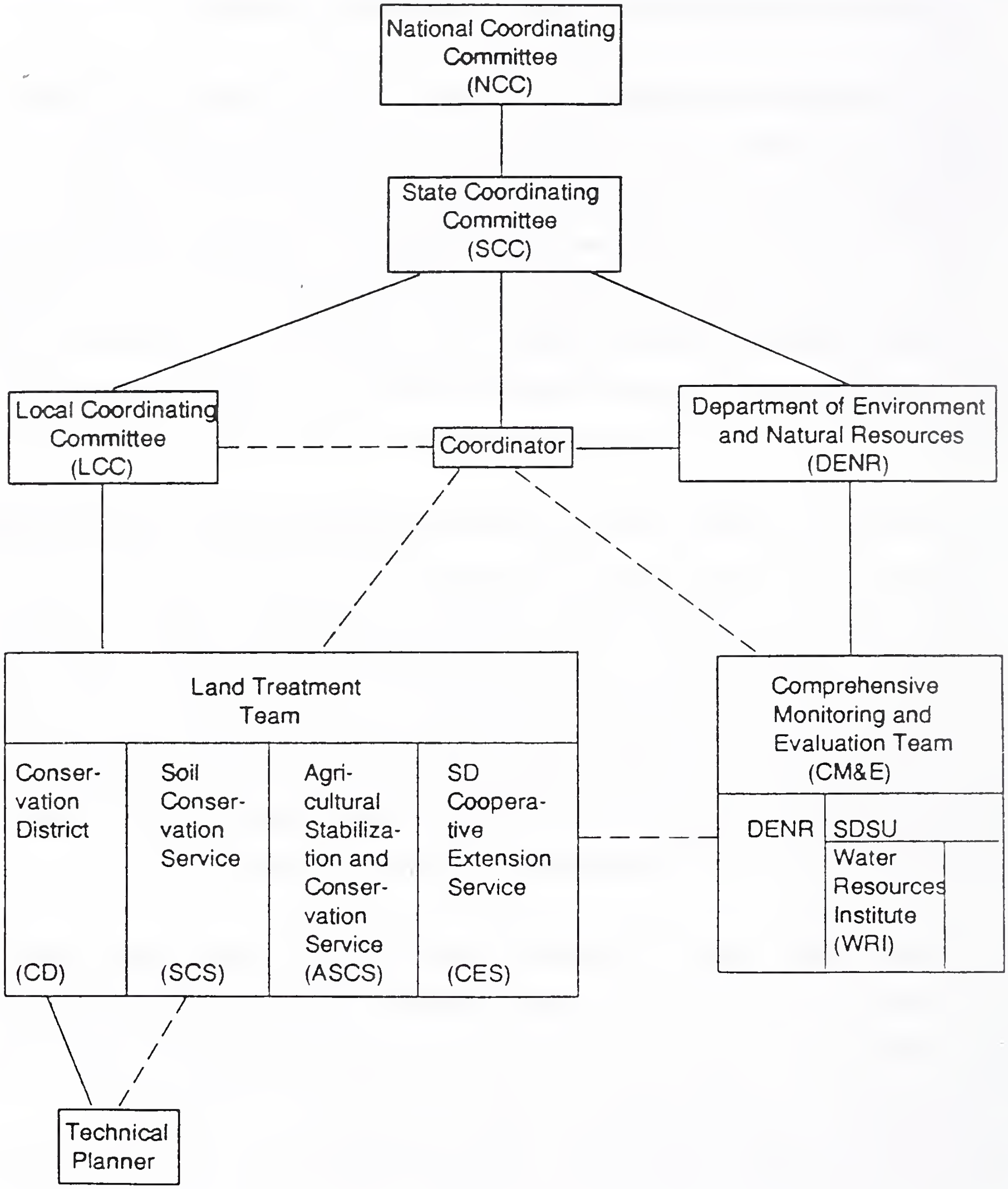

Figure 1. Oakwood Lakes-Poinsett RCWP project organizational chart.

working relationship with project teams and committees. Some project managers may just coordinate activities. Others may be actively involved in project tasks.

Potential participants in the organizational structure should include:

- Water quality monitoring entity (the state water quality/environmental agency, university, private contractor)
- Land treatment agency (Natural Resource Conservation Service, Consolidated Farm Service Agency, Conservation Districts, university)
- Information and education entity (Cooperative State Research Education and Extension Service, university, private contractor)
- Landowners/operators
- Community leaders
- Environmental groups
- Adversely affected water users
- Public

Other agencies such as financial institutions, Economic Research Service, Realtors, statistical reporting groups, and others may provide information on measurements to determine the socioeconomic impacts of the project. The role of each participant must be clearly defined to avoid confusion, duplication of effort, and competition between participants.

It is important to include local landowners in the project organizational structure to ensure community acceptance and support for the project. Landowners that may be encouraged to change their land use practices must support and accept the objectives of the project. Local participation and support provide a feeling of local ownership in the project, which cannot be provided by outside agencies. It is critical for the project leadership to be sensitive to the landowners' needs.

Individuals that are part of the organizational structure should believe in the project and maintain active participation throughout the project's duration. These individuals can make or break a project, so they should be carefully chosen. These individuals must have support from their agency management and be given the time and resources necessary to carry out their agency's or group's responsibilities. It is important for individuals to eliminate the need to protect their personal or agency role and for them to come together for the success of the project. Formal agreements should be used to ensure the successful completion of the workplan within the scheduled time lines. Role conflicts may be avoided if all project funds are distributed through one agency or through the coordinating committee for the project.

Communication is an essential element in the effectiveness of institutional arrangements. Active participation by individuals, agencies, and groups provides a mechanism for communication. Electronic communication such as computer bulletin boards and e-mail and facsimile machines also enhance project communication. Computer data bases that are compatible and transferable to all entities will also help in more efficient project evaluation and report writing.

Lessons Learned from RCWP

- **A full time project coordinator living near the project area is an asset and provides a link between teams and coordinating committees.**

- **All participating agencies and organizations should be involved in the implementation of a workplan that includes a unified reporting system and the allocation of resources.**

- **A close working relationship between water quality and land treatment teams is essential, particularly in the early stages of the project, to ensure**

best management practices are applied where appropriate to improve or protect the targeted water resource.

- **Financial incentives will likely be necessary to ensure landowner participation.** The organizational committees will need to secure funding for this and for other activities including monitoring at the very beginning of project planning. Federal, state, local, and private funds or resources may be needed.

- **An information and education program is essential for the successful completion of a project, and an information and education team would be helpful to the coordinating committees.**

- **Information and education and economic evaluation activities should be initiated early in the project.**

- **Contacts with other RCWP projects, both formally and informally, were helpful to the projects' leadership.**

- **One-on-one contact with landowners increased their implementation of best management practices.**

- **Data bases for project information should be developed early in the project and must be compatible and transferable between agencies.**

- **Local coordinating committees were successfully used in several RCWP projects by providing local support, priority setting, and project planning.**

- **State coordinating committees were successfully used in many RCWP projects by providing communication with the National Coordinating Committee, maintaining initiative and enthusiasm for projects, and ensuring adequate resources to meet project objectives.**

- **Occasional field days, tours, barbecues, and demonstrations helped to maintain interest in the projects and increase landowner participation.**

- **Lack of project understanding can hamper landowner participation and community support.** A bad experience for one landowner with the project can discourage other potential project participants, which can hamper project success.

Case Studies from RCWP

South Dakota - Several characteristics of the Oakwood-Poinsett RCWP project administration were a key to the project's success. A technical planner was hired early in the project to make one-on-one contacts with the area landowners. This increased the participation in the project from six (6) farms to 121 farms in one year. A project coordinator that was given the time and responsibility to work on the project also contributed to continued communication between the various agencies and individuals involved in the project. The project coordinator was also more effective when the person was located near the project area.

Local and State Coordinating Committees and the land treatment, water quality, and report writing teams, were identified as successful administrative tools for project management (Figure 1). Contracts and formal agreements between the funding agency and the land treatment and monitoring agencies were effective in keeping the project on track and for evaluating project progress (Kuck and Goodman, 1992).

The information and education and the socioeconomic evaluation programs would have been more effective if the funding for those activities had been distributed at the state level. Field trips, project tours, and monitoring demonstrations were used to explain the monitoring and land treatment aspects of the project. Landowners, government agency staff, local government officials, and other monitoring project personnel were the audience for the information and education activities. These field activities helped to generate support for the project and for future nonpoint source pollution projects. It also helped to build grass roots support for future county water quality ordinances and state environmental protection legislation related to nonpoint source pollution and ground water quality protection. The focus of the information and education program changed from working with area landowners and the public in the project's early stages, to transferring project results outside the project area in the later stages (Goodman et al., 1991).

Nebraska - Three subcommittees formed by the Local Coordinating Committee contributed to Nebraska's RCWP project success. The three committees were the Information and Education Committee, the Technical Advisory Committee, and the Executive Committee. Project personnel reported that the project suffered from insufficient communication between the State and Local Coordinating Committees, and from the lack of a designated full-time project coordinator. Dedication of agency staff earlier in the project also would have helped the project (Hermsmeyer, 1992).

Pennsylvania - The Conestoga Headwaters project benefitted from excellent project management that was attributed to effective lines of communication and interagency coordination. Strong support of the Local Coordinating Committee by the State Coordinating Committee provided flexibility to the local management of the project. This flexibility helped to overcome difficult social and economic issues that prevented landowner participation. Different approaches to project participation were approved by the national funding agencies because of this state and local support (USDA-ASCS, 1991).

WATER QUALITY MONITORING

Purpose

Water quality monitoring is important to nonpoint source pollution control projects because it is the measure of the land treatment effect on the water resource. Each monitoring project will be different, but monitoring may meet several needs. USDA-NRCS (in press) lists the following purposes for monitoring:

> To analyze trends in water quality characteristics;
> To study the fate and transport of pollutants in water;
> To define critical areas within watersheds exhibiting greater pollution potential than other areas;
> To assess compliance with water quality plans or standards or water pollution control permits;
> To measure effectiveness of conservation practices or pollution prevention;
> To evaluate program effectiveness in the project area;
> To make wasteload allocations for different pollutant sources;
> To test computer models;
> To conduct research;
> To define a water quality problem.

Not all these types of monitoring are needed or appropriate for every project. The types of monitoring used will depend on the complexity of the project and the project's objectives.

Water quality monitoring can provide information when developing a project. For example, monitoring plays an important role in **problem identification**. Monitoring for this purpose must begin either before project development or early in the project development process. It

will help identify the following: 1) the specific impairments to the water body, 2) the major pollutants, 3) the sources of the pollutants, and 4) the seasons or times of year when pollutants are most evident.

Water quality monitoring will also affect how land treatment and land use monitoring is conducted. Both water quality and land use monitoring are required to establish a relationship between water quality changes and land treatment. A feedback loop that transfers water quality monitoring information to the land treatment team can improve project implementation. Identification of areas with the largest contributions of contaminants, or times when the worst problems occur allows targeting of best management practices. Water quality monitoring can also change the focus of the project if some management practices are shown to be more effective than others as the project progresses.

Water quality monitoring is also important to overall project evaluation. The objective of most projects will be to document the water quality impact of actions taken by land users to reduce nonpoint source pollution. Project evaluation is often based on documentation of water quality benefits. This is important to the project's funding entity, the individuals making the management changes (land users), local sponsors, and users of the water resource. Documentation of project success is important for continued support of such projects by these groups.

Planning the Monitoring System

Before monitoring begins, a monitoring plan must be developed. Some elements of the plan will be established in the project development process. These elements include identification of the water quality problem, agency roles (who does the monitoring), and the water resource to be monitored. A complete monitoring plan should also include:

- clear objectives
- study design
- size of area to monitor (scale)
- parameters to be analyzed and analytical methods
- monitoring site selection
- instrumentation and sampling techniques
- quality assurance and quality control procedures
- evaluation techniques
- reporting requirements
- budget

The group developing the monitoring plan must include specialists such as hydrogeologists, engineers, chemists, and, depending upon the project's objectives, can include soil scientists, limnologists, biologists, and others. Monitoring a hydrologic system will involve teamwork among the specialists and may require combining different types of monitoring. For example, ground water monitoring and vadose zone monitoring could be used to establish that a cause and effect relationship existed between ground water quality and best management practices. Ground water monitoring could be used to detect changes in water quality in the ground water resource. Vadose zone monitoring could be used to document the mechanism by which the land treatment activity could affect the ground water quality. Both would be needed to establish a cause and effect relationship.

Developing Monitoring Objectives

The monitoring objectives should state what needs to be done to accomplish the desired result. The amount of monitoring that can be done will be limited by the available funds. Developing monitoring objectives should follow the same procedure as developing project objectives (see Project Development Section). An example of a monitoring objective is:

"To determine + the effect of implementing conservation practices + on nitrate concentrations in the Big Sioux aquifer."

Most projects will have more than one monitoring objective. Once the objectives have been written, the relationship between them is defined, and the priority and order of completing each objective should be determined. **The monitoring objectives should support the overall project objectives and must address the identified water quality problem.**

Once established, the monitoring objectives should serve as a guide while developing the monitoring program. Development of the monitoring plan elements should be consistent with the objectives.

The monitoring objectives should also serve as a reference to allow periodic reassessment of the monitoring program. Adjustments in the monitoring program may be needed if it is learned that the original monitoring plan will not meet the objectives. There may be concerns about producing an inconsistent data set if the monitoring program is changed. Consistency in data collection is important. However, if the original monitoring program will not meet the objectives, the data will be of little value even if it was collected consistently throughout.

Selecting Monitoring Study Design

Once the monitoring objectives have been completed, a strategy or experimental design to accomplish the objectives must be established. The study design will be selected based on the monitoring objectives, and it will help determine the appropriate scale and location of monitoring sites. The study design will describe: 1) the structure of the experiment to learn how changes in water quality will be detected, and 2) what statistical methods will be used to decide if changes occur.

Many ground water studies employ a variation of upgradient versus downgradient design. Sara (1991) discusses several variations of this design. Most of the designs discussed by Sara (1991) are intended to detect ground water contamination from a regulated facility (point source), such as a landfill or a hazardous waste site. USDA-NRCS (in press) devotes a chapter on monitoring study designs used on nonpoint source projects. Study designs discussed include the plot, single watershed, above-and-below, two watershed, paired watershed, multiple watershed, and trend station. Most of the USDA-NRCS (in press) discussion pertains to surface water studies but some study designs are applicable to ground water monitoring. A summary of each USDA-NRCS study strategy and how it could be used for a ground water monitoring project follows.

Plots

In this design, small areas of a field are replicated several times to study the effects of a practice. The information is compared to a control plot, which is monitored like the others but does not receive the treatment or practice. Advantages of using plots are that the design has a control, and several statistical tests are available to determine if significant differences exist. A disadvantage of using plots for ground water studies is that a treatment applied to a plot may have little effect in the ground water compared to other inputs. The results are also not likely to be transferable to the project area as a whole (USDA-NRCS, in press).

Plots may not be useful to evaluate the effect of a practice on ground water. However, plots can be used to study the mechanisms of transport from the land surface to the ground water. In the South Dakota RCWP project, valuable information on the rate and timing of contaminant movement through the vadose zone was obtained using a modified plot design.

Single Watershed

In this design a single watershed is studied before and after a practice has been applied to evaluate the practice. The single watershed design is not recommended by USDA-NRCS (in press) because the water quality effect caused by the practice cannot be separated from the water quality effects of other factors such as climate. An advantage of this design is simplicity and low cost.

For ground water studies, a single aquifer design could be used to evaluate changes in aquifer water quality over time. The single aquifer design would be most useful if: 1) water quality data for the area were available for a long period before applying practices over the aquifer, and 2) a similar post-practice study period was possible. Some effects due to climate may be accounted for if several wet and dry years were included in the before and after period. Using the design in this way for ground water is similar to the use of the trend station design (below).

Trend Station

This design involves the study of a single watershed over a long time. Practices are installed over a period and are evaluated using a variety of statistical techniques to detect trends in water quality data. A control watershed is recommended which has no changes in land use (not converted from cropland to pasture for example) or land management practices. Advantages include the simplicity of the design and the ease of finding sites. A disadvantage is that over such a long study period, unwanted changes may occur in the study area or control watershed that will also affect water quality (USDA-NRCS, in press).

For ground water studies, finding a "control" aquifer is very difficult. Defining the land area that is affecting water quality in the aquifer is also a problem. Water quality changes in aquifers due to land use changes occur more slowly than similar changes in surface waters. This requires a longer study period. It may be difficult to secure funding to conduct a 10 or 20 year study.

Two Watersheds

The use of two watersheds, one with best management practices and one without, is not recommended by USDA-NRCS (in press). There is no calibration period before practices are installed. Therefore, the water quality differences between two watersheds (or aquifers) caused by the practice, and differences caused by geology, soils, or other characteristics, cannot be separated.

The two watershed design poses significant challenges for a ground water monitoring project. The watersheds should be very similar on the land surface for surface water studies, but should also be similar below the land surface for ground water. Sites that are homogeneous geologically and mineralogically where the flow systems are well defined but not connected are necessary for the design to be successful. This may be very difficult to attain and appropriate sites will be limited in number. It may also require an extensive exploratory drilling to define the sites' geology and hydrology.

In the South Dakota RCWP project, ground water quality was monitored at a nonfarmed site to define the variability in contaminant concentrations in the absence of any disturbance due to farming. Specific management practices could not be evaluated in this way, but "natural" changes in water quality that may have affected other sites were used in the evaluation. Large variability in water quality was observed in shallow wells at the nonfarmed site. This

suggested that small water quality changes due to best management practices would probably not be detected over the background variability.

Paired Watersheds

The use of paired watersheds differs from the two watershed designs in that the two watersheds are monitored before and after implementation of practices. During the before or calibration period, the watersheds are treated alike. Following the calibration period, best management practices are applied to one watershed and not the other. Data evaluation is by regression analysis of the before and after periods. This is a recommended design (USDA-NRCS, in press) that was used successfully to evaluate manure management practices in the Vermont RCWP Project (Meals et al., 1990).

The problems associated with the two watershed designs are also true of the paired watershed design in its application to ground water studies. Although this design may be useful for some ground water studies, finding appropriate sites may be difficult.

Multiple Watersheds

The multiple watershed design uses several watersheds with practices, and several without to study the water quality effects of best management practices. Advantages include the transferability of the data to the entire project area, and that the variability between sites is included in the variance for each treatment. Disadvantages for surface water include the difficulty of timing sampling with field runoff, and the cost of calculating annual mass loading for each site (USDA-NRCS, in press).

In ground water studies, monitoring costs for multiple watersheds could be prohibitive because of the large number of sites needed with many wells at each site. If one assumes an

individual site with numerous wells represents the study area, this strategy may be useful. In some cases, particularly when background data are available prior to installation of the facility (application of a practice), intrawell comparisons may be used (each well is compared to its own history). The advantage of this approach is that it eliminates the spatial component of variability from the comparison. Several statistical approaches are possible depending on the distribution of the data (Lesage and Jackson, 1992).

Above-and-Below Watersheds

This design involves monitoring above and below the location of a best management practice and analyzing the difference in water quality between the two stations. Although conducted in a single watershed, this design effectively creates two watersheds, one within the other. Advantages of the above and below design is that year to year climate variability makes little difference. Disadvantages of this design are: 1) downstream water quality may be a function of upstream water quality, and 2) differences between upstream and downstream water quality may be due to factors other than the practice under study (USDA-NRCS, in press).

If above and below monitoring is conducted before and after the best management practice is installed, it can be analyzed as a paired watershed design (USDA-NRCS, in press). Above and below, and before and after designs were successfully used in the South Dakota RCWP project to evaluate the water quality impact of building an animal waste management system at a feedlot located on a small tributary.

Ground water monitoring using this design is called upgradient versus downgradient monitoring. This is probably the most commonly used strategy in ground water studies and should be used as part of most designs. Upgradient wells are placed on a site in a location that can yield ground water samples that are not affected by the practice. Downgradient wells are placed to detect changes due to the practice as close to the practice as possible. Placement

of the wells is important because ground water sites are three dimensional. Gradients in the vertical as well as the horizontal direction must be known. Due to geologic heterogeneity at some sites, water may not always flow directly from upgradient to downgradient. Up and down gradient directions may vary with time and other factors. For more information about placement of wells, refer to the GROUND WATER MONITORING SECTION.

Quantification Stations

Most nonpoint source study designs are used to determine whether water quality changes can be attributed to implementation of best management practices. Other study designs may also be applicable depending on the needs of the project. For example, the need may arise to quantify pollutant loadings unrelated to changes in best management practice.

Quantifying pollutant loads involves measuring the quantity of water moving past the monitoring point and the concentration of one or more pollutants in the water. The concentration multiplied by the water volume equals the mass of the pollutant. Different methods are used to measure the volume of water or pollutants. The method used depends on whether ground water, tributaries or atmospheric sources are measured, but they all answer the question of "how much?"

Determining the quantity of pollutants can be used to compare the relative contributions of different pollutant sources. These may include:

-surface water versus ground water sources
-tributary loadings versus internal lake loadings
-point source versus nonpoint source

Often this information is needed to put the effects of a project into perspective. Relative contribution may be important if expected changes in water quality are not observed in the targeted water body. For example, a hypothetical project has predicted a 50% reduction in phosphorus loadings due to a specific best management practice using a paired watershed design. That practice was widely applied but no improvement in lake water quality was observed. Additional monitoring indicated that a point source accounted for 90% of the loadings to the lake; no change in lake water quality would be expected from land treatment alone. If any other source is large compared to the one the project is designed to control, there is little chance of documenting water quality improvements.

Selecting an Appropriate Scale

As the monitoring plan is developed, the size of the area to monitor must be decided. Monitoring objectives, available resources, and the complexity of the project will determine the size of the area. Three types of study areas to consider are: plot, field, and aquifer scale. Aquifer scale may be similar to watershed scale in surface water studies. There may be other size study areas to consider, depending on the needs of individual projects. Scale must be consistent with the time frame and funding limits of the project. **After the scale of the study area is decided, it should be reevaluated to ensure the scale is consistent with the monitoring objectives.**

Monitoring costs, variability in the data, and the potential for documenting change will be affected by the choice of scale. Selecting a small plot may allow evaluation of a single land use practice on a homogeneous site at reduced cost, variability, and time. As the scale of the monitoring area increases, the variability of the data increases, and a longer time for monitoring may be needed. The cost of monitoring also increases as the time and quantity of data increases.

Plot Scale

Plots may be useful to: 1) evaluate the fate and transport of contaminants, 2) determine the effectiveness of a conservation practice, 3) calibrate a model, or 4) solve a specific research question. **Careful control of the practice being evaluated is an advantage of plot scale studies.** Plot scale monitoring may have a greater probability of detecting water quality changes attributed to specific land use practices. Variability in the data should be less since a plot should be more homogeneous than the project area as a whole. Costs and the time needed to evaluate a specific practice are also reduced. A disadvantage of using plots is the uncertainty of applying what is learned to the larger area of interest.

Field Scale

Monitoring on a field scale usually covers a larger area than an individual plot. Field scale monitoring sites may include the entire field or part of a large field. Field scale monitoring is appropriate for evaluating individual practices on a field. It may be more representative of the water quality effects of operational farming practices than monitoring experimental plots. **The information on the water quality effects of best management practices at a field scale may be more transferable to the larger project area or other aquifers within the region.** The cost of monitoring a field-scale project can be less than either plot studies or monitoring a large region of an aquifer. Disadvantages include the difficulty of finding landowners that will allow monitoring on their fields.

Aquifer Scale

A larger project scale than either plots or fields is needed if the monitoring objective is to detect long-term trends in an aquifer. **Monitoring an aquifer can provide information on the general characteristics of the water quality of an aquifer and may provide seasonal,**

temporal, or long term trends over a large area. A disadvantage of aquifer scale monitoring is the difficulty of attributing specific land use changes to water quality changes within a reasonable time. For most individual best management practices, aquifer scale is not an appropriate scale of study.

Selecting Parameters

The selection of water quality parameters requires consideration of several factors. The tendency is to analyze more parameters than are necessary. Water analyses are expensive, and resources committed to measuring unnecessary parameters will limit the scope of the monitoring project in other ways (fewer sites, fewer samples, shorter project, etc.). **A large suite of parameters on a few samples can help describe basic characteristics of the water. A small suite of parameters on many samples may be more cost effective to detect changes in contaminants over time.**

Some parameters may relate directly to the water quality problem. For example, high nitrates are identified as the water quality problem, and fertilizer management is selected as a best management practice. Then, measuring nitrate concentrations in the vadose zone and ground water would be important to establish a cause and effect relationship. Other parameters may be selected for their explanatory value. For example, dissolved oxygen concentrations in the ground water may indirectly effect nitrate concentrations and can help "explain" variations in nitrate concentrations unrelated to fertilizer management. Other parameters may be used to characterize the system and identify the likely source of water in areas where more than one aquifer is present. This may not be necessary in surface water studies where the flow system can be observed directly. However, it is useful in ground water studies where much about the nature of the subsurface is inferred from indirect observations during drilling and with analysis of water quality parameters.

The appropriate form of the contaminant to measure is another consideration. Dissolved nutrients may be important to all systems. Particulate forms of nutrients, while useful for lake, stream, and wetland systems, are not meaningful for soil or ground water systems. The difficulty and cost of analysis are usually higher when low detection limits and a high degree of precision are required. Criteria for detection limits and precision and accuracy necessary to document change in the parameter of interest should be considered when selecting methods of analysis.

Efficiency is also a consideration. Scanning for pesticides using gas chromatography can efficiently detect several pesticides, including metabolites, in a single analysis. The cost per pesticide quantified is low for a broad scan but high if only one or two pesticides are needed. Immunoassay can be a cost-effective way to quickly identify the presence of a specific pesticide. If several pesticides are to be identified, many individual immunoassay tests on each sample may not be cost effective. It can be a good screening tool but quantification limits may not be acceptable and verification should be done by gas chromatography or other methods.

When water quality parameters are highly related but the analysis cost of one is much lower than the other, the parameter with the less expensive analysis could be selected. For example, two parameters used to characterize aquifers, electrical conductivity and total dissolved solids, are often highly correlated. Substituting electrical conductivity, which can be measured in the field, can save laboratory costs.

Selecting Monitoring Sites

The question of "where to sample?" is critical to a successful monitoring program, but it is not a straightforward question in most nonpoint source monitoring projects. In point source monitoring, the location of the pollutant discharge relative to the stream, or the spill site

location relative to the aquifer, will determine where monitoring will occur. The diverse nature of nonpoint source pollution prevents the location of sampling sites at the point where the targeted water resource is affected by the contaminant. The impact on the resource may also be more gradual or less pronounced at any given sampling point when compared to point source pollution. Detecting water quality changes due to reductions in nonpoint source pollution is usually more difficult than changes due to reductions in point source pollution.

Selection of ground water monitoring sites differs from selection of surface water monitoring sites. Watershed boundaries, flow restrictions, and channel characteristics are readily determined in surface water studies. It is difficult to determine similar characteristics of a ground water site. Defining the direction of flow is more complicated for ground water, and the flow direction can change. Ground water flow across heterogeneous sites will not be consistent in direction or rate and can differ from the regional flow direction.

Geology is the major influence controlling ground water flow (Sara, 1991). The geology of an area that is to be monitored must be adequately assessed to define the flow system at the site. As the heterogeneity of a site increases, accurate determination of the geology and hydrology becomes more difficult, and more site evaluation will be required. This is of particular concern in glacial materials. **Installing monitoring equipment before adequately evaluating a site may lead to a waste of monitoring resources.**

Defining the portion of a project area contributing recharge to a particular aquifer and locating recharge areas may be difficult. Learning where the contaminant originates and how it reaches the impacted water body is a major challenge for nonpoint source ground water monitoring projects. At the point where ground water is sampled, a contaminant may have traveled through the air to the site, in surface water from another site, percolated through the vadose zone, or traveled to the sampling point via ground water movement. To characterize ground water, several sampling locations and depths may be required. **As the number of**

sampling stations increases, the number of samples at each station must decrease to remain within a set budget.

The method of deciding on sampling locations will be different for each project. Sampling locations depend on the characteristics of the aquifer under study, the project and monitoring objectives, and the monitoring study design. Other factors such as land owner cooperation may further limit potential sites. Depending on the individual land owner and his needs, large fields may not be available for study. Farming around wells on a field for several years can limit a landowner's willingness to cooperate. Placing wells in many locations on several fields is probably not practical though that may be the best study design.

Frequency of Monitoring

The frequency and length of time to sample depend on the nature of the system monitored and the purpose of monitoring. It will be affected by the water quality variability of the system and aquifer characteristics such as infiltration and percolation rates and vertical and horizontal hydraulic conductivity (i.e., how fast does water move through the aquifer material). The hydrologic characteristices of the system also effects variability. Nitrate concentrations in a confined aquifer are expected to have less variability than soil water in the vadose zone, for example.

Frequency of ground water sampling will also vary depending on the monitoring objectives. Water quality data collected before a change in land use are needed if the objective is to establish a linkage between the land use and water quality changes using a before and after study design. To detect changes in an aquifer over time, infrequent sampling for a long time would be appropriate. To detect movement of contaminants and document the contaminant arrival in the aquifer, frequent, event-based sampling in the vadose zone and at the water table would be required. To determine loadings of contaminants from ground water to surface

water, frequency may vary seasonally with changes in flow and concentrations of contaminants.

Frequency is also dependent on other factors that affect the contaminants under study. Intensity of recharge events, seasonal changes, the timing of pesticide and fertilizer applications, and land disturbance activities all can affect how often sampling should be conducted. Frequency of sampling and how long sampling continues ultimately depends on the available budget. It must be balanced with other needs, such as number of sites or parameters analyzed. USDA-NRCS (in press) presents several methods for calculating the sampling frequency needed for specific types of statistical analysis and sampling techniques. Many of the examples given are for surface water monitoring situations but can commonly be applied to ground water monitoring. Although these types of calculations are useful, they should not be used to replace the expert judgment of a hydrogeologist familiar with the geological setting.

Lessons Learned from RCWP

- **Attempting extensive monitoring with too little money will usually result in useless data sets that will not contribute to meeting monitoring objectives.** If the budget is insufficient to complete the monitoring objectives, the objectives should be reevaluated and parts of the study design changed (before submitting the project for funding). For example, fewer parameters should be measured or fewer sites should be sampled.

- **How each parameter will be used in data evaluation should be critically evaluated.** If a parameter is not needed to support the monitoring objective or if its value to the evaluation of other parameters cannot be explained, it should not be measured.

- **The key to the successful location of monitoring sites is to know where the ground water is coming from, where it is going and where it discharges to surface water bodies of interest.** Unfortunately, this can only be estimated until some monitoring data is collected.

- **Planning a monitoring program is essential, but reevaluating and revising the program during the project is equally important.**

- **Monitoring other variables such as surface water discharge, precipitation, ground water table elevation, and impervious land surface area is often important in accounting for water quality variability.**

- **More control over the land management practices that may affect water quality is possible when monitoring small research plots compared to privately owned farmed fields.**

Case Study from RCWP

South Dakota - In the Oakwood Lakes-Poinsett RCWP project, there was considerable debate about the wording of the monitoring objectives. Coffey and Smolen (1990) suggest that monitoring objectives should specify the anticipated result of a change if management practices change. In the Oakwood Lakes-Poinsett RCWP project, the result of the management practices could not be anticipated. It was not known if conservation tillage to control erosion would increase or decrease nitrate and pesticide concentrations in the aquifer. It was not reasonable to state an objective for a specific reduction in contaminant concentrations. Therefore, a null hypothesis was stated that there would be no change in nitrogen and pesticide concentrations in the aquifer. The monitoring objective was to

disprove the null hypothesis. If there was evidence of a significant change in ground water quality, the null hypothesis would be rejected.

Several study scales were used. A plot scale was used to investigate transport mechanisms and rate of nitrate and pesticide movement through the vadose zone to the water table. Field scale monitoring was used to determine the effect of conservation tillage, fertilizer management, and pesticide management on ground water quality. The size of the field sites ranged from 20 to 80 acres. Aquifer scale was used to determine the interaction between surficial aquifers and the Oakwood Lakes. Although this is not typical of aquifer scale monitoring, the measurement of ground water as it enters a lake is similar to measuring the discharge of a river into a lake. In this situation, aquifer scale is similar to a watershed scale of monitoring for surface waters.

Extensive drilling to characterize the overall project area and to evaluate potential field sites was conducted before final selection of monitoring sites. Final site selection was affected by site geology and land owner cooperation. Individual sampling points were located upgradient, downgradient and within field sites.

Sampling frequency in some cases was modified from regular intervals to event-based sampling. This was done to detect changes in the aquifer from recharge events that occurred more rapidly than originally estimated. Frequency was also increased during the growing season to better evaluate land treatment effects on water quality as knowledge of the hydrologic system increased.

QUALITY ASSURANCE/QUALITY CONTROL

Purpose

To ensure the analytical data from water quality samples are of the highest quality, quality assurance/quality control measures are required. The actions are preventive in nature and are required from the very beginning of the project through completion.

Standard Methods for the Examination of Water and Wastewater describes quality assurance as "a set of operating principles that, if strictly followed during sample collection and analysis, will produce data of known and defensible quality" (APHA, 1992). The Environmental Protection Agency describes quality assurance as "an integrated system of activities involving planning, quality control, quality assessment, reporting, and quality improvement to ensure that a product or service meets defined standards of quality with a stated level of confidence" (US EPA, 1994).

How to Develop Project Quality Assurance

If a project is undertaken with state or federal funds, a quality assurance project plan will be required. Preparing a written document for quality assurance is recommended for any monitoring project, despite the funding source. A quality assurance plan provides a written description of the project's who, what, when, where, and how the quality assurance measures will ensure the results meet the expectations of the project planners (Vitale et al., 1991).

A quality assurance plan should be prepared by the water quality monitoring team. It should include all the activities of the monitoring project and the activities of the water quality laboratory. A quality assurance plan should begin with details that occur during the drilling

and construction of monitoring wells and continue with details of the physical collection of water samples, the handling and analysis of water samples in the laboratory, and the computer entry and management of the analytical data. In most cases, a separate quality assurance plan will be prepared by the laboratory for all laboratory procedures. The laboratory plan should be reviewed by the water quality monitoring team to ensure the needs of the project are met. The laboratory quality assurance plan should be included in the complete project plan.

The Environmental Protection Agency has a standard format and required components for a quality assurance plan (US EPA, 1994). *Standard Methods for the Examination of Water and Wastewater* also recommends minimum elements to address in a plan (APHA, 1992). These components describe the objectives concerning: data quality, project management and responsibilities, measurement/data acquisition procedures (sampling protocols and analytical techniques), assessment and oversight for quality assurance, data validation and usability, and reports to management.

The first thing that should be decided by the project's monitoring team is the data quality objectives. This can be done by answering the question: "How good do the data need to be to meet the purpose and objectives of the project?" For example, if the sampling results will be used to determine compliance with permit requirements, data quality objectives may be higher than if the sampling is done to define the general characteristics of a water resource.

Standard operating procedures for all components of the project should be available in a written document that may be a part of, or attached to, the quality assurance plan. The detail and care in these activities depend on the most sensitive parameters such as volatile or synthetic organic compounds versus inorganic constituents. For example, if pesticides are the primary parameters of interest, care taken during drilling, well construction, and sampling should be geared toward those parameters. **The standard operating procedures should include the following:**

- drilling
- monitoring well construction
- collection of water samples
- field instrument calibration
- equipment de-contamination procedures
- preparation of quality assurance samples

The laboratory hired to conduct the analysis of the water samples should be chosen carefully. There are several questions to be asked of the laboratory during the contracting or bid letting to address quality assurance/quality control issues (Eastwood, 1995):

- Is the laboratory instrumentation up-to-date?
- Does the laboratory have up-to-date computer equipment?
- Is the computer support personnel knowledgeable about new computer products?
- What is the quality of the laboratory's information management system, i.e., can analytical results be directly input into the computer?
- What is the caliber of employees employed by the laboratory?
- Does the laboratory have quality assurance/quality control procedures, are they followed, are they updated, and are they periodically checked?
- Is the laboratory certified by an outside certification program and is the laboratory certified for the parameters of interest in the project?

Following are some suggestions for project managers before contracting with a laboratory (Eastwood, 1995):

- Talk to the account executive.
- Call the laboratory manager.

- Read over the information provided by the laboratory regarding their services.
- Obtain a list of current certifications held by the laboratory.
- Obtain a list of qualified personnel currently employed by the laboratory.
- Obtain a list of current, satisfied customers of the laboratory and contact them for information.
- Take a tour of the laboratory, preferably with an experienced chemist to give an opinion of the laboratory's practices.

The specific analytical technique for each parameter and the appropriate holding times for samples should be specified in the laboratory contractual agreement and in the quality assurance plan. Protocols for data recording and storage should also be developed, and necessary equipment (computer hardware and software) must be purchased early in the project, preferably before sampling begins. Computers make this step easier than in the past, but data entry must be carefully done.

Lessons Learned from RCWP

- **Review quality assurance results regularly to correct any problems and prepare a final quality assurance report as part of the final project evaluation.**

- **Blind spike samples are very useful tools to measure the accuracy of the laboratory results.** Commercially prepared spike samples, however, may be difficult to obtain for new pesticides.

- **Duplicate samples are a useful indicator of laboratory precision.** Duplicate samples are only useful, however, when parameters are consistently found. Duplicate samples were not useful for pesticide analyses in the South Dakota

RCWP project because most of the water samples had no detectable concentrations of pesticides.

- **The drilling equipment should be cleaned between boreholes. If the water samples from the wells will be analyzed for low concentrations of pesticides, the following should be done: 1) drilling equipment should be steam cleaned, 2) well casing should be steam cleaned or purchased already cleaned and wrapped, and 3) gravel pack should be cleaned and bagged.** This can eliminate questions of data accuracy for infrequent organic chemical detections.

- **Two seepage meters installed in the same location at some sites and measured simultaneously can be used to estimate the variability of seepage measurements between instruments.**

- **Two consecutive measurements from the same seepage meter can be used to estimate the error involved in collecting individual seepage measurements.**

Case Study from RCWP

South Dakota - The Oakwood Lakes-Poinsett RCWP project used standard, industry accepted methods for well drilling and well construction. Improvements in quality assurance were made during the life of the project as new technology and knowledge were obtained. The standard operating procedures for sampling the monitoring wells were documented and used to train sampling personnel. These standard operating procedures included the number and frequency of blank and duplicate samples and were used throughout the life of the sampling activities. There were two laboratories used in the South Dakota RCWP project,

and the laboratories were required to prepare quality assurance plans for the project. Contracts with the laboratories were written for the life of the project. The contracts included the number of samples, frequency of sampling, the analytical method to be used, and the cost for each analysis. In the last few years of sampling, input of analytical results into the computer database by the laboratory helped to eliminate input errors. Spreadsheet data bases were used for the storage of chemical data.

LAND USE - MONITORING

Purpose

Land use monitoring is essential to link land treatment and water quality changes. Land use monitoring involves collecting data on the type of land treatment applied to the study area and other land use activities that may affect water quality, such as type of crop grown or tillage practices. Both land use and water quality data collected in a coordinated plan are needed to detect causes of observed water quality changes. The effects of climatic factors that affect water quality, such as rainfall, temperature, soil moisture, frost formation and thaw, and others must also be accounted for.

How to Collect Land Use Data

The methods for land use data collection vary with the needs of the project. The methods used should be established early in the project by members of both the water quality monitoring team and the land treatment team. There are several sources of land use data: observations taken during water quality monitoring, windshield surveys, information from land owners or operators, and existing information such as Consolidated Farm Services Agency aerial photos. For plot studies, land treatment may be part of the experimental design.

Observations made during the regular water quality monitoring schedule can provide site land use information without bothering the land owner or operator during busy times of the year. Important information such as crop type, crop stage at the time of sampling, and residue left after tillage can all be obtained in this manner. A useful format to collect this information is to prepare a map of each monitoring site and the surrounding fields. Field boundaries, crops and other information can be written on the map. Blank lines for date, observer and other pertinent information should be included.

The windshield survey is similar to observations made while sampling but on a larger scale. It is useful to identify cropland, non-cropland, crop type, residue after tillage, and other visual factors in large study areas or where information is unavailable from the land owner. If windshield surveys are combined with Consolidated Farm Services Agency aerial photos, quantitative data (number of acres) from a wide area can be collected quickly and inexpensively. The aerial photos are taken each year for farm program compliance checks, so land use data can be updated yearly from the photos. Photocopies of the aerial photos for each section of land are also available. Writing land use information directly on these photocopies and then adding field boundaries later with current slides is a convenient way of recording windshield survey data.

Major advantages of the windshield survey are: 1) the consistency of the data is controlled by the observer, 2) it is inexpensive to obtain, and 3) it does not require obtaining records from individual land operators. However, disadvantages of the windshield survey include lack of information on events that occur infrequently or quantitative information that cannot be collected visually. Some areas cannot be observed without cooperation from the landowners.

Data which cannot be collected by windshield survey include: 1) timing of pesticide and fertilizer applications, 2) amounts of chemicals applied, and 3) other specific data that must be collected from the operator. If possible, the land operator should keep a record of activities.

The best data will come from the person performing the activities while keeping good records. Some producers will not keep records, the data may be incomplete, or the data will lack the level of detail or exact information needed.

Data obtained through field observations, windshield surveys, personal interviews, and Consolidated Farm Services Agency photos can be managed in a GIS (Geographic Information System) format. GIS is a computer program or manual process that allows spatial data to be displayed in layers. A base map of the area must be prepared with identifiable features such as road intersections, fence lines or other landmarks as the first layer. New layers are added by registering these features on aerial photographs with the known location. In this way, data collected by windshield surveys can be set to scale using the Consolidated Farm Services Agency slides and digitized on the GIS base map.

A GIS system can be used to simply catalog land use data and display it, but a more powerful use is analysis of spatial data to calculate new information. Data from several years can be analyzed, quantified, and displayed. For example, the number of acres planted in continuous corn for three years could easily be quantified and mapped. Distribution of these areas compared with monitoring sites or water quality data could also be shown. A GIS can be used to show the juxtaposition of several factors that affect water quality. An example is including areas with heavy manure applications on thin soils overlying shallow aquifer areas.

Using a GIS system for managing land use data such as crops or tillage practices can be labor intensive because of the need to digitize many layers of data. Also, layers need to be updated as changes occur. However, if the project requires a summary of data spanning several years or an analysis of the **data to evaluate combinations of several factors** is needed, the time may be well spent.

Data evaluation and reporting also affects land treatment monitoring. Land use data should be reported early in the project and included in all reports to help identify deficiencies in the data set. Early attempts at analysis to establish links between water quality monitoring data and land use data may lead to refinement of both land use and water quality monitoring efforts. Both the water quality monitoring team and the land treatment team should be involved in the reporting and refinement process. Changes can be made in water quality or land use monitoring procedures to correct identified deficiencies. The value of early and regular data evaluation cannot be overstated.

Lessons Learned from RCWP

- **Water quality data and land treatment data should relate to the same study area over the same time period if water quality changes are to be linked to land treatment.**

- **Collecting land treatment data on practices likely to effect the specific contaminants identified in the problem statement and are the focus of the water quality monitoring program, is required to link water quality changes to land treatment changes.**

- **For small scale plots, land use and the practices applied can be carefully controlled by project personnel.** This reduces the variability in the land use component and may increase the chances of linking land use and water quality changes.

- **Contacting landowners in person during a time that is convenient for them will encourage them to keep good records.** It is best not to bother them

during planting and harvesting, particularly in years with unfavorable farming conditions such as drought or flooding.

- **Collecting land use and water quality monitoring data before a change in land use is necessary to establish a linkage between the land use and water quality data (before/after design).**

- **The linkage of land treatment to water quality can be made at the research plot, farm field, aquifer scale or project level.** However, the larger the scale, the more difficult it is to establish the linkage, and there is less predictability.

- **Smaller is better if the project objective is to document water quality impacts of land treatment in a short period with a limited budget.**

Case Studies from RCWP

Vermont - The St. Albans Bay RCWP project conducted extensive land use monitoring for individual watersheds within the project area. Location and timing of land treatment practices and location and size of contaminant sources (dairies) were recorded. Quantitative data such as rates of manure application were also tracked. The project used a checkbook system to make it easy for landowners to record information. The Vermont monitoring team also reported that the paired watershed design was the most effective design to link land treatment and water quality. Small watershed size allowed the evaluation of the water quality impact of winter manure spreading within a short period of time.

South Dakota - The Oakwood Lakes-Poinsett RCWP project used small field sites to study land treatment effects on ground water. The project also used research plots to study

movement of contaminants through the vadose zone. A small study area simplified the land use data set since usually only one or two crops and pesticide or fertilizer regimes were present at each site. Data on crops near each well were recorded in a table that was completed by personnel collecting water samples. Data collected annually through interviews with the land owner or operator of each field site were recorded in a field notebook. The land use variable was simplified on the vadose zone plots since crop and management were carefully controlled by the researchers.

In the South Dakota RCWP, some landowners were reluctant to contribute information on practices, especially fertilizer and pesticide use. The land owners were concerned about telling state officials details of their operation, possibly due to fear of regulatory action even though RCWP was an entirely voluntary program.

PROJECT EVALUATION

Purpose

Documenting the success of a project is important for several reasons. Public support for future projects to control nonpoint source pollution depends on documenting positive water quality changes. If current methods are not working, other ways to deal with nonpoint source pollution are needed. If projects are successful, knowledge gained through project evaluation and documentation can be used by future projects to control nonpoint source pollution. Evaluation can also be important to the project's successful completion if conducted throughout the life of a project. Evaluation can be used to refine land treatment and water quality monitoring efforts if a feedback loop between the monitoring team and the land treatment team is effective.

Nonpoint source pollution projects by definition focus on water quality impairments due to diffuse sources of pollution. Therefore, the main objective of most nonpoint source projects will be to improve or protect water quality with best management practices. Evaluation of water quality data with land use and other data, is necessary to document attainment of this primary objective.

Evaluation of water quality data need not be the only measure of the success of a project. Another measure of success is to determine what was completed during the project compared to what was proposed in the workplan. This type of evaluation may be the only measure of success if water quality monitoring was not a component of the project.

How to Evaluate Project Success

Project Evaluation

What will be a successful project should be defined in a written proposal by clearly stating the objectives and the methods to accomplish them. The project workplan should list each task, who is responsible for each task and when the task will be completed (see Project Development). Progress toward completing the workplan serves as a measure of success.

Each task within the workplan can be evaluated to determine progress that can be stated as the percentage of the task completed. For example, the following activities that were completed in a given time frame and within a fixed budget, can help measure the success of the Information and Education part of the project by comparing them to the tasks in the workplan: listing the number of people contacted, pamphlets developed and distributed, workshops held, public meetings, tours, and other activities. It would be difficult to quantify the success of this endeavor without documenting the number of products produced.

Other aspects for monitoring the success of the project might include:

1) the number of acres where land treatment was implemented
2) the number of information and education products produced
3) the percent of landowners/operators adopting best management practices
4) documented water quality improvements
5) documenting positive economic impacts to landowners/operators of alternate management practices on profitability
6) impacts of water quality changes on the ecosystem and society
7) development of new water quality monitoring techniques/instruments/ systems
8) contributions to the knowledge base of nonpoint source pollution
9) a change in attitudes about water quality, best management practices, and nonpoint source pollution by people in the watershed as measured by surveys

Some aspects of project evaluation may be related to primary project objectives. Others may be ancillary to the project. All known effects of the project should be included in the evaluation. Sometimes a project may have unintended negative consequences that should also be included in the evaluation.

Some impacts of a project may not be easily evaluated. Publicity surrounding the project itself may raise the visibility of a water quality problem and increase public concerns or response. There may also be acceptance of best management practices beyond the project boundaries, which may improve or prevent deterioration of other water quality bodies not targeted by the project. Therefore, there may be intangibles that cannot be quantified in the evaluation process. If these changes are long-term effects of the project, they can be extremely important.

Water Quality Evaluation

Unlike the evaluation of land treatment objectives, it is insufficient to count the number of samples collected and parameters analyzed to determine the success of a monitoring project evaluating ground water quality. The water quality changes over the life of the project should have some correlation to the change in a single variable - land treatment/management.

The purpose of the collection of water quality data is to provide useful information to decision-makers concerned with land management policy and/or clean water policy. It is critical that the data are evaluated scientifically to determine correlations or relationships in the data. The stronger the relationships, trends, or correlations between water quality and land use changes are developed, the more trust decision-makers can put into the information from the project. It should be understood that field or watershed scale projects have more variables that are not under the scientist's control as compared to laboratory or plot studies. This potential confounding of variables lowers the scientist's ability to determine strong relationships between land treatment and water quality changes.

Evaluating changes in water quality is one of many ways to measure a project's success. However, it is the only way to answer the question, "Did the project meet the water quality objectives?". The ultimate goal of water quality data evaluation is to determine if changes in water quality can be attributed to project activities. This implies that a cause and effect relationship exists and can be documented. This is probably the best measure of a project's success, but may not be possible for many projects. Other types of water quality data evaluation may be used to infer the success of a project even if documenting cause and effect is not possible.

Reasons for data evaluation are:

1) Characterizing the resource (descriptive): Evaluation of water quality and other data to describe ambient conditions of the resource system is useful. It provides a better understanding of the hydrologic system that simplifies subsequent data analysis and provides a foundation for conclusions. Descriptive analysis of basic hydrologic characteristics, dominant ions present, and geological settings would be appropriate for all water bodies. For lakes, descriptive analysis might also include structure of fish, plankton and invertebrate populations, vegetation present, temperature and oxygen stratification, and overall trophic state. For aquifers, describing vertical and horizontal gradients, rate of water movement, porosity, hydraulic conductivity and other basic hydrogeologic information would be important. Describing potential beneficial uses of the resource can also help focus data analysis on factors that affect those uses.

2) Detecting differences: Data evaluation can be used to detect spatial or temporal differences in water quality data. If data are uniform or randomly variable so that significant statistical differences cannot be detected, further analysis is limited. Statistically significant changes in water quality over time or at different sampling points are necessary for further analysis. Further analysis is necessary to reach conclusions about factors that might be related to the changes or differences in water quality.

3) Ranking the relative contributions to a water quality problem: Observed differences in water quality may be used to determine the relative importance of contributors to a water quality problem. This might include point source versus nonpoint source, ground water loadings versus surface water loadings, feedlot runoff versus septic tank discharges, or internal versus external loadings to lakes. This type of evaluation will be important if a major change in water quality is due to a point source in the

nonpoint source project area, or if internal loadings in a lake are greater than external loadings.

4) Documenting mechanisms by which land use practices affect water quality: Evaluation of water quality data from plot or laboratory studies can be used to infer how water quality may be affected on a larger scale. Documenting these mechanisms can also be used to establish cause and effect relationships. It may be possible to establish a cause and effect relationship between land use and water quality if: 1) the observed differences and changes in water quality form a significant pattern, 2) mechanisms have been documented to show water quality was affected by these factors, and 3) the effect is consistent. Association, consistency, responsiveness and mechanism are all needed for causality (USDA-NRCS, in press).

5) Using data as input to a model: Another way of evaluating data is to use a model to make predictions about water quality changes that may result from the project. Modeling involves using a series of equations to represent flow and transport mechanisms that affect movement of pollutants through the system. These equations are solved to develop an estimate or a simulation of real world water quality impacts. Modeling results are predictive tools and should be verified with water quality monitoring.

The study design and nature of the data will determine the type of evaluation that is used. Methods of data evaluation include:

1) Visual analysis: The first step in data analysis should be visual inspection of the data. This will provide a better understanding of subsequent statistical tests or modeling efforts that may be conducted. There are several ways to visualize the data. A plot of the data will help determine if data is normally distributed or skewed, identify outliers,

and suggest patterns, trends or random arrangement of the data. The data can also be presented in tables to simply look at differences in the data. USDA-NRCS (in press) refers to this process as exploratory data analysis and refers to a number of techniques that may be used. These include: writing the numbers (tables), stem-and-leaf diagrams, schematic summaries, transformations, comparisons, plots of relationships, and smoothing data. Other visual techniques useful for ground water data evaluations include: trilinear diagrams, geologic cross-sections, geologic mapping, isopleths, water table contours, and geologic groupings (geozones).

2) Statistical analysis: Although visual analysis gives an indication of what the data shows, specific statistical tests are needed to confirm differences or trends. The type of statistical analysis that may be used will be determined by the study design. For example, the above-and-below design is analyzed as a t-test of the difference between paired observations (if normally distributed) (USDA-NRCS, in press). Statistical tests can also be used to test a hypothesis, determine if there is significant difference, and detect trends. Statistical tests can also be used to determine central tendency (means or medians) and variability (standard deviation).

The data must also meet basic underlying assumptions before specific statistical tests can be used. USDA-NRCS (in press) devotes a chapter to statistical assumptions that must be valid to use certain statistical tests. They include: randomness, normality, homogeneity of variances, independence, and additivity. Tests to determine these assumptions are also discussed.

Different statistical methods are used for data that are normally distributed, rare event data (Poisson) distribution, or for which the data is unknown or atypical (nonparametric). Robert D. Gibbons provides an overview of statistical methods and criteria for selecting the appropriate statistical method based on distribution of the data

(Lesage and Jackson, 1992). The presentation is geared toward waste disposal facilities but can be applied to nonpoint source studies. Others useful references include "Statistical Methods for Ground Water Monitoring" (Gibbons, 1994) and "Organization and Analysis of Water Quality Data" (Sara and Gibbons, 1991).

3) Numerical Modeling: Project evaluation through modeling involves inputting data to a model based on established relationships and processes to arrive at a conclusion. Modeling can be used as a predictive tool, estimating tool, or used to identify critical areas. The primary assumption when using numerical models is that the predicted conditions are a close approximation of the actual field conditions. This may or may not be true, so field testing is necessary. A major limitation of models is the large amount of data required to develop and calibrate them.

4) GIS (geographical information system) analysis with geostatistics: Geographical information systems can be used with geostatistics to describe and estimate various features of spatial data sets. Geostatistics is a method used to describe the spatial continuity that is a feature of many natural phenomena. Classical regression techniques are used to analyze spatial information in earth science data sets. Issaks and Srivastava (1989) describe various geostatistical tools, what they can do and their limitations. A case study is used to show the use of continuous variables such as thickness of a geologic horizon, pollutant concentration, soil measurements, permeabilities, rainfall measurements, and discrete variables that are one of the two possible categories. These variables are used to describe features of the data, estimate average values, estimate distribution and uncertainty of the estimates. Geostatistical techniques were developed for mining applications, but can also be used to evaluate spatial data sets generated by nonpoint source projects.

Linking Land Treatment with Water Quality

A key to successful project evaluation is to document that water quality was improved. A consistently improving trend in water quality after the implementation of best management practices may show water quality improvements attributable to land treatment. Water quality improvements at multiple field monitoring sites and the lack of similar changes at non-best management practice sites provides strong evidence that water quality improvements resulted from land treatment.

Documenting a relationship between land treatment and water quality changes depends on a good experimental design for water quality and land treatment monitoring. Detecting significant or real trends in water quality and land treatment, and linking water quality trends with land treatment trends are two objectives that must guide the monitoring study design and data analysis in projects intended to link water quality changes to implementation of best management practices (Gale et al., 1993). Single or multiple best management practices may be evaluated by monitoring study designs as paired watershed, upstream/downstream monitoring before and after land treatment, and multiple watershed monitoring (see Water Quality Monitoring section).

Water quality monitoring before best management practice implementation is necessary to document baseline conditions. Post-land treatment monitoring data are required to statistically compare to baseline data. Because aquifer water quality changes often occur slowly, long term monitoring efforts of five to 10 years or longer may be needed to confirm real, consistent changes that can be linked to land treatment.

Land treatment and land use monitoring are necessary to link water quality changes to land treatment (see Land Treatment Monitoring section). As found in the RCWP projects, the larger the drainage area or the area contributing water to a monitoring point, the harder it is to

establish the linkage (Gale et al., 1993). Land treatment data should be reported in quantitative units such as application methods, tons of manure spread per acre, pounds of fertilizer applied per acre, acres tilled by each tillage practice, rates of pesticides applied, and others. Land use and land treatment data must often be summed over a large area to match the area influencing the water quality data (Gale et al., 1993). Land treatment and land use data should be managed spatially to match the water quality monitoring such as by aquifer area or by watershed.

Land treatment and water quality data should also match on a temporal scale. Land treatment data can be added to the trend analysis as repeating explanatory variables. Water quality data can be aggregated to the same time scale as the land treatment data for analysis (Spooner et al., 1995).

Besides monitoring best management practices and pollutants of primary concern to the project, the monitoring of other explanatory variables may be necessary to strengthen the link between water quality changes and land treatment. The explanatory variables, such as stream discharge, precipitation, and ground water table depth, may help in accounting for variability in water quality, land treatment, and land use data. Explanatory variables should be factored into trend analyses to document water quality trends. This analysis may be more indicative of trends than those that would have been measured had no changes in climatic or other explanatory variable occurred over time (Spooner et al., 1995).

Lessons Learned from RCWP

- **It is important to develop sound baseline information before or early in the project from which to measure future changes.**

- **Land use and agricultural management practices in the project area should be documented before the implementation of any best management practices.** This pre-project monitoring can also serve as a baseline from which to compare any land use changes and water quality impacts.

- **It is important to evaluate the accomplishments of the project regarding achievement of the objectives during the early phases of the project.**

- **A strong correlation between water quality changes caused by implementation of best management practices must be established and observed changes must be repeatable over time and space (Spooner et al., 1995).**

- **A statistically significant correlation or relationship between land treatment and water quality changes is required to show a cause-and-effect relationship.** An association by itself is not sufficient to infer a cause-and-effect relationship; other factors such as rainfall or change in land use may cause changes in water quality (Spooner et al., 1995).

- **Documenting the assumptions used in calculating the acres served is important so that these units can be calculated consistently from year to year (Spooner et al., 1995).**

- **A high level of appropriate nonpoint source pollution control implementation in critical areas is usually required to achieve substantial water quality improvements.**

- **The large volume of data collected from water quality and land use monitoring will require appropriate data base management tools.**

- **Before using statistical analysis to evaluate water quality data, consultation with a statistician familiar with nonpoint source projects and the type of data sets typically produced is recommended.**

Case Studies from RCWP

Idaho - There were high sediment loads to Rock Creek caused by irrigated cropland runoff and streambank erosion. This high sediment load reduced salmon spawning, recreational use, and fishing. Evaluation of the success of the project was based in part on the percent of critical acres in ten subbasins contracted for best management practices. Success ranged from 52% to 105% of critical areas under contract in the subbasins (USDA, 1991). The experimental design for chemical monitoring included upstream and downstream monitoring of subwatersheds and portions of Rock Creek. Monitoring of these areas for fish populations, chemical concentrations, and sediment loads before and after best management practice implementation indicated that sediment ponds and streambank stabilization improved downstream water quality.

Florida - Upstream and downstream monitoring of total phosphorus in several subwatersheds and at the main creek outlet before and after best management practice implementation indicated there was a 50% reduction in total phosphorus to Lake Okeechobee due to the applied best management practices upstream. The seasonal Kendall Tau test was used to determine trends for water quality data that were positively skewed. Results were influenced by the length of record and the number of samples collected each season (Stanley and Gunsalus, 1991).

Vermont - A paired watershed approach was used to document the effect timing manure application (winter vs. summer) had on nitrogen and phosphorus concentrations and loads in field runoff. The statistical approach used was the development of regression equations that described the relationship between control and treatment watersheds established during the calibration period. Nutrient concentrations were predicted using the regression equations. Data evaluation was based on differences in predicted nutrient concentrations and the concentrations which were observed following treatment.

REPORTING AND INFORMATION DISSEMINATION

Purpose

Periodic reporting of project progress and results is necessary for several reasons. Reporting documents the complete project and what was learned and accomplished. It also helps similar projects and presents the results to the public (Smolen, 1991). Distributing the information gained in a project can be very effective in educating the public in water quality issues. It also provides a mechanism for project leaders to reevaluate project objectives and to modify project priorities. **Reporting documents water quality improvements and other benefits of nonpoint source pollution control, which is necessary for continued support and funding for this type of environmental protection activity.** Decision-makers can use the information for future nonpoint source pollution abatement and prevention projects.

How to Report and Disseminate Information

Regular review of information and progress helps to ensure that the project is working toward its objectives and that the project activities are on track (Gale et al., 1993). Quarterly report writing may be cumbersome, and complete analysis is not possible at such a frequency. However, quarterly progress summary reports and meetings of the project leadership,

especially during the initial years of the project, are effective in communicating progress and in making adjustments as necessary.

Annual progress reports, as required in the RCWP projects, create an opportunity to compile and analyze findings (Gale et al., 1993). Project staff may resist preparing annual reports because it is time consuming. The benefits of the reports, however, are apparent in the later stages of the project. Annual reporting also provides the opportunity to adjust project priorities. If it is shown that certain parts of the project are not effective, the preliminary data are in error, or landowner participation is low, project objectives may be refined. Annual progress reports should be scheduled during the non-field months to allow field personnel adequate time to do data evaluation (Goodman et al., 1991).

Reporting should be planned for and should be included in the project's workplan. Resources to complete data evaluation and reporting must be included in the project's time frame and within the project budget. Reporting plans should include a periodic self-evaluation of the project (Kuck and Goodman, 1992).

Designating one project person to manage the preparation of the report is helpful, particularly when there are several authors preparing different sections of the report. It is important to use compatible computer equipment and software to simplify final report preparation. It is also important to maintain communication between writers to ensure the report is progressing on time and there is no duplication of efforts.

Reports should be done in a standard format developed during project planning and should involve people doing the field work. The format of the report will vary according to the intended audience. The contents of the report should include information that is not too technical for program administrators and the general public. However, the reports must also include adequate information that will be useful for other water quality projects and

environmental and land treatment agencies. Project managers may even consider the preparation of two different reports targeted for two different audiences, one for decision-makers and one for scientists.

Lessons Learned from RCWP

- **Exchange of annual reports with other RCWP projects stimulated self-evaluation and project development.**

- **Time, staff, and funding for reporting and report publishing need to be budgeted and included in the initial project workplan to ensure adequate reports are prepared.**

- **Annual reports, more frequent updates, and periodic (every 2-5 years) comprehensive reports are needed to provide for feedback to project leadership.** This allows modification of the project as needed.

- **A standard reporting format for the RCWP projects was helpful because it provided a complete documentation of project activities and a consistent evaluation of the program.**

- **Time can be saved in preparing a new format by reviewing various report formats and selecting one that meets the needs of a project.**

- **Reports are most useful when succinct and limited in size by using visual representations of the information such as graphs and tables.**

- **Executive summaries that include the most important points and results of the report are useful for decision-makers who have limited time to review the report.** Key pieces of information in an executive summary may decide continued support of the project by this audience.

Case Study from RCWP

South Dakota - The Oakwood Lakes- Poinsett RCWP project annual progress reports were thorough, more timely, and better written when project management prepared two reports, one administrative and one technical. The administrative report was prepared according to the funding agency's required fiscal schedule, and the technical report was prepared during the non-field work months. This allowed the monitoring and land treatment teams the time necessary to evaluate data and prepare written reports (Goodman et al., 1991).

GROUND WATER MONITORING

INTRODUCTION

There are many references on ground water monitoring available, some of which are listed at the end of this section. Most references, however, focus on monitoring point sources of pollution or monitoring to determine the extent of contaminated ground water. Nonpoint source pollution studies may consist of monitoring ground water that is not contaminated, has very low levels of contamination, or has variable contaminant concentrations. The objectives of nonpoint source pollution studies may be to determine the success of changing land use practices over a large area and the resulting change in ground water quality. Although literature related to point source monitoring is useful in nonpoint source studies, applying the lessons learned from the RCWP projects can benefit project sponsors by saving time and money.

The need to monitor ground water will vary with the type of project and the water quality problem. The tools for monitoring ground water are the same for point and nonpoint sources of pollution; the extent of the monitoring, however, may vary and will usually be more complex for a nonpoint source pollution study.

Ground water monitoring can be done in combination with vadose zone and surface water monitoring and, depending on the study objectives, should be done to identify the entire hydrologic system. If the objective of a project is to determine the effectiveness of applied land use practices in protecting ground water resources, ground water and vadose zone monitoring is necessary to define the fate and transport of contaminants. The ground water and surface water should be studied together if the project's objective is to: 1) determine the wasteload allocation to a stream or lake, or 2) determine the most effective method of lake, stream, or watershed protection/remediation.

The monitoring objectives of the South Dakota RCWP project were to:

- define the ambient ground water quality and any changes in ground water quality due to the implementation of agricultural best management practices;
- evaluate the effects of tillage practices and cropping on the percolating water in the vadose zone; and
- estimate the effects of watershed best management practices on the lake water quality in the Oakwood Lakes system.

This chapter describes the process to monitor ground water to determine the effects of nonpoint source pollution control. Steps for **pre-project planning and monitoring system design, monitoring system implementation, and ground water data management and evaluation** are presented. Project objectives will determine the details and extent to which each step of the process is applied. The details from the Oakwood Lakes-Poinsett RCWP project that are applicable to the process are also discussed. Some examples from the South Dakota RCWP project are given for various steps, and key lessons learned are highlighted at the end of each discussion. These were chosen because of the applicability to other nonpoint source projects, because of the cost of doing it wrong, or because of the time it can save.

PRE-PROJECT PLANNING AND MONITORING SYSTEM DESIGN

The water resource will be characterized and the system to monitor the water resource will be designed, during this stage of the project. Careful planning and appropriate monitoring study design will result in the collection of quality data and success in meeting the monitoring objectives.

The steps in pre-project planning and monitoring system design are: **1) choose a monitoring study design; 2) collect background data and choose potential monitoring sites; 3)**

collect additional data; 4) design the monitoring well system; 5) select the parameters to be measured; 6) choose sampling methods and equipment; and 7) determine the sampling frequency.

Choose a Monitoring Study Design

The design of the monitoring study will depend on the scale of the monitoring. The scale can be aquifer-wide, site-specific, or plot scale. The project objectives and available funding will determine the monitoring scale necessary for the project. Nonpoint source pollution problems can affect entire aquifers. However, aquifer-wide ground water monitoring could be cost-prohibitive and difficult to evaluate because of the many variables affecting water quality. Plot scale monitoring would be useful because the study conditions can be controlled, but the monitoring would be more research-oriented. The data may be questioned because the monitoring did not reflect "real world" situations. Site specific monitoring on farmed fields may provide data more reflective of actual conditions but at a scale small enough to be equipped cost effectively.

There are many types of monitoring study designs as discussed in an earlier section (page 33). The terms used in describing these designs usually relate to surface water studies, but some design concepts can apply to ground water. Study designs such as reconnaissance, before and after, above and below (upgradient and downgradient), and paired watershed, can be used in ground water monitoring studies. Reconnaissance monitoring can be used in an aquifer-wide or regional study to assess background water quality or to describe changes in water quality over time. Before and after, paired watershed, and above and below (upgradient and downgradient) designs can be used in a field scale monitoring study where a change in land use is implemented.

There are several considerations when using these designs. By definition, the quality of ground water entering the site (upgradient) and leaving the site (downgradient) must be identified in the above (upgradient) and below (downgradient) monitoring design. It is also recommended upgradient and downgradient monitoring be used in the before and after, and the paired watershed designs because land use upgradient of the monitored site can influence the monitoring results.

If ground water is readily influenced by land use, the land use management upgradient of the monitoring site should be controlled or substantially different than the land use management on the monitoring site. This should be done to adequately evaluate the water quality differences attributable to differences in land use management. If controlling the upgradient land use is not possible, any water quality change due to land use management changes cannot be attributed solely to that change. For example, if a farmed site is monitored upgradient and downgradient of a best management practice, but an area upgradient of the monitoring site has a similar practice, any water quality changes due to the practices may not be detectable.

The concepts of all three designs may be combined. Field-scale monitoring sites should be equipped with upgradient and downgradient wells. Wells should also be located within the site and located along the ground water flow paths. Monitoring would take place during a calibration period before best management practices were implemented to define the natural variability of the water quality. After the calibration period, best management practices would be implemented on the farthest downgradient portion of the site, with a mid-field well(s) becoming the new upgradient monitoring site. Monitoring would continue on the entire site. As in all monitoring study designs, it is very important to monitor sites that are as geologically homogeneous as possible.

The South Dakota RCWP project used seven field sites between 20 and 80 acres in size. Ground water quality was monitored upgradient and downgradient on field sites where conservation tillage, fertilizer management, and pesticide management practices were applied. The management practices had been implemented prior to monitoring; therefore, before and after monitoring was not possible. One field site farmed without best management practices was used to compare with the sites where best management practices were implemented. Comparisons were difficult to make since the water quality and geology were so variable at each site, and the land use management upgradient of the field sites was similar to the practices at the field sites. Land use management would have to be different or to change substantially, such as from crop land to pasture land, to show a water quality change.

One field site that had not been farmed for over 20 years was also used as a "control" site to provide a comparison of water quality beneath an unfarmed area. This site was helpful during project evaluation. The data from this site demonstrated the extent of natural water quality variability in glacial sediments unaffected by farming practices.

Steps to take in choosing the monitoring study design and lessons learned in the South Dakota RCWP project are:

- **Choose a monitoring study design based on the project objectives, scale, and geology.** If the geology in the project area is too complex, the number of monitoring sites that can be adequately characterized for the chosen study design, may be limited.

- **To ensure the monitoring system design is valid, begin the monitoring well before the practices are installed.** Best management practices were already implemented before monitoring was initiated in the South Dakota RCWP project, so before and after monitoring was not valid.

Collect Background Data and Select Potential Monitoring Sites

Information on water quality, geology, and hydrology in the project area is needed to define the hydrologic system that will be monitored. There are several sources for this type of information. Table 1 lists some common data sources, the information they provide, and where to find the information.

The criteria for potential monitoring sites should be based on the monitoring objectives. When the existing data are compiled, areas that meet the criteria can be identified for further work.

In the Oakwood Lakes-Poinsett project, the first indication of a ground water quality problem was a report of domestic wells with nitrate concentrations exceeding the safe drinking water standards. Geologic maps; a limited database of water quality information from domestic wells; county soil surveys; geologic logs from domestic wells, observation wells, and test holes; hydrologic information from two previously conducted studies; and some limited land use data were available for the project area. The information was compiled and plotted on 1:24,000 scale maps.

The ground water monitoring objective was to determine the effects of changing land use management practices on the quality of ground water beneath farmed fields. When initially choosing potential monitoring sites, it was assumed the most rapid and greatest effects would be in the shallow ground water in sand and gravel deposits. Sites with no confining layers and where land was tilled and agricultural chemicals were used, were needed. Therefore, using maps, potential monitoring sites meeting these criteria were identified in areas of thin, permeable soils and shallow sand and gravel deposits.

Table 1. Background Data Sources.

DATA SOURCES	INFORMATION PROVIDED	WHERE TO FIND
Geologic maps	Surficial geology/aquifer boundaries Sensitivity/vulnerability	US Geological Survey State Geological Survey State Natural Resources or Water Quality Agency
Hydrogeologic studies	Aquifer characteristics Sensitivity/vulnerability Ground water flow direction/gradients Potential recharge areas Surface water/ground water connections Water quality Water table depths	US Geological Survey State Geological Survey State Natural Resources or Water Quality Agency Universities Consultant Reports Permit Applications
Public water supply reports	Water quality Well construction Geology/Hydrology Aquifer characteristics	USEPA State Drinking Water Office Individual water suppliers
Domestic well logs	Water quality Well construction Water table depths Geology	State Natural Resources or Water Quality Agency US Geological Survey State Geological Survey Well drillers
Soil surveys	Soils characteristics Aquifer vulnerability	US Dept. of Agriculture
Climatology reports	Precipitation patterns Frost depth	US Weather Service State Climatologist
Land use maps	Crops grown Crop rotations	US Dept. of Agriculture Universities

Steps to take in collecting background data and choosing potential monitoring sites, and lessons learned from the South Dakota RCWP project are:

- **Research all available data.** In the South Dakota RCWP area, the South Dakota Geological Survey was the source of many well logs and water quality analyses; water level data were available from the state water appropriation agency. Nitrate and bacteria analyses from hundreds of domestic wells were available from the state drinking water regulatory agency. However, the incidence of high nitrate concentrations from domestic wells was not representative of ground water in the area because of the location and construction of the domestic wells.

- **Organize the data into a usable data base.** If a Geographical Information System is available, the data can be plotted, compared, and layered for further assessment. A Geographical Information System was not available to the South Dakota RCWP project, so the data were compiled on maps. These maps depicted deposits and thicknesses of likely water bearing formations (outwash), watershed boundaries, soil characteristics, ground water quality, and other relevant data from the project area.

- **Establish criteria for potential monitoring sites based on the monitoring objectives and any assumptions made during the pre-project planning.** Criteria used in the South Dakota RCWP project were: shallow outwash deposits with no confining layer, thin soils, cropped land with agricultural chemical application, and land owner cooperation.

- **If the existing data are adequate, choose potential monitoring sites based on the established criteria for further data collection and refinement. If**

the data are inadequate, identify areas for field work to collect the needed information.

KEY LESSON LEARNED: Use caution when evaluating domestic well data to determine ambient water quality. Domestic wells are often located near point sources of contamination on farmsteads and can be high in contaminants that are not related to nonpoint source pollution. Conversely, wells that are screened into the lower portions of the water bearing formation and not at the water table (for example, irrigation wells) may not indicate a nitrate problem. In an unconfined aquifer system, contaminants originating from the land surface are most easily detected near the water table.

Collect Additional Data

Existing information for a project area may be limited. If so, collecting additional field data may be necessary to adequately define the hydrogeology of the area or sites to be monitored. If existing information is adequate to choose potential monitoring sites, additional site-specific data may be collected to prepare the final design of the monitoring system. Test hole drilling, monitoring well installation, and water quality sampling can be done to define the following: geology, depth to ground water, ground water gradient, and existing water quality at potential monitoring sites.

In the Oakwood Lakes-Poinsett RCWP project, background data were adequate to choose potential monitoring sites. Preliminary test holes were drilled, monitoring wells were installed, and samples were collected at the potential monitoring sites. Split-spoon samples of the subsurface materials were collected during the test hole drilling to provide a detailed geologic description of each field site. These samples were invaluable in defining the complex glacial geology of the sites and provided the mechanism to describe potential contaminant occurrence and transport at each site. Monitoring wells were constructed at potential monitoring sites where landowners had agreed to cooperate in the study. The wells

were used to establish ground water flow directions, gradients, and water table depths, and to provide preliminary water quality information. This information was necessary before the final monitoring system at each field site could be designed.

Steps to take in collecting additional data and lessons learned in the South Dakota RCWP project are:

- **Contact the landowners of all potential monitoring sites.** Landowners may be leery of the purposes for monitoring and may decline to cooperate if they feel threatened by regulatory compliance based on the outcome of the monitoring. In the RCWP project, several alternate sites had to be evaluated because of the reluctance of landowners. Also, the criteria for site selection had to be redefined to include glacial till sites since there were not enough sand and gravel sites located where land owners were willing to cooperate in the study. In cases where objectives allow random placement of monitoring wells, road right-of-ways and public lands may be acceptable.

- **Conduct test hole drilling (drilling methods are described on page 94) and collect continuous soil samples from two to three test holes at each field site to verify or further define the geology of potential monitoring sites (Figure 2).** Several potential sites were drilled in South Dakota, even more than were needed for the project. Once the drilling rigs were available, as much data as possible were collected in the case the sites did not meet the criteria for site selection. This saved in costs for remobilizing the drilling rig.

- **Construct a few monitoring wells and survey the measuring points on the wells.** If a site meets the selection criteria, at least three monitoring wells should be constructed at the site to define the ground water gradient and flow

Figure 2. Split spoon sample.

direction. Nested wells can be constructed to define the vertical component of the ground water flow. Nested wells are wells constructed at different depths at the same location (Figure 3). Several textbooks, such as *Ground Water* by Freeze and Cherry (1979) and *Groundwater and Wells* by Driscoll (1986), describe methods to determine ground water flow direction and gradient.

- **Collect water samples from the newly constructed monitoring wells to document existing water quality at the site.**

- **Identify any point sources of contamination at or near the monitoring sites.** For any given contaminant of concern, look for all sources of the contaminant. For example, if nitrate is a concern, potential sources of nitrate such as feedlots (both active and inactive), septic system drainfields, haystacks,

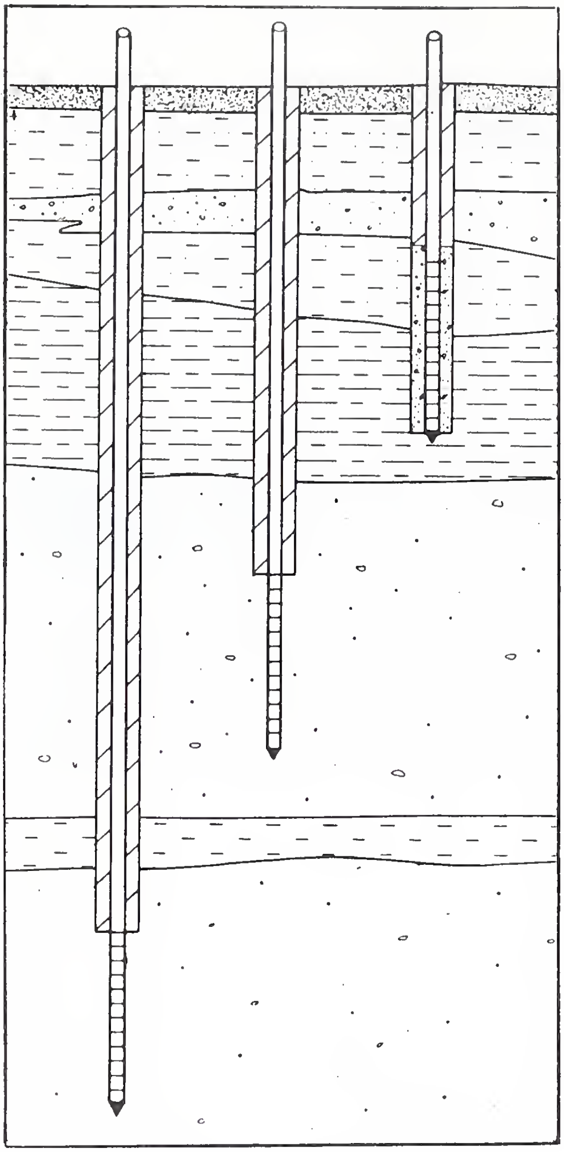

Figure 3. Schematic of nested wells.

silage piles, and fertilizer storage and mixing areas, should be identified. Abandoned wells can also serve as point sources of contamination from runoff and intentional dumping. Two wells initially installed in the South Dakota RCWP project had to be removed from the monitoring network because of the influence of a point source of pollution on the ground water quality. The source was an abandoned feedlot.

- **Document existing land use practices at the sites to ensure the monitoring objectives for the site will be met**. In the South Dakota RCWP project, the monitoring was done to determine the effect of implementing conservation tillage, fertilizer management, and pesticide management on ground water quality. Monitoring sites with row crop farming and agricultural chemical use were needed. These sites then needed to undergo a change in management practices. Sites where best management practices were already in place could serve as control sites, i.e., for comparison with sites without best management practices. These sites could not be used as before and after implementation studies.

- **Choose the final monitoring sites and obtain long term access to the site for the duration of the monitoring study.** In the South Dakota RCWP, access to the monitoring sites was secured with easements between the land owners and the conservation districts. Payments ranged from $100-250 per year to offset the loss of crops and the inconvenience of farming around wells.

KEY LESSON LEARNED: In situ (split spoon) sampling at frequent intervals provided detailed information on the complex glacial geology of the monitoring sites. This sampling later proved invaluable in the monitoring system design and data evaluation. A unique classification system called "geozones" was developed for the study. The classification system was based on the geology of the field sites and used to reduce the variability of the water quality data (see discussion of geozones on page 116).

KEY LESSON LEARNED: The limiting criterion for monitoring site selection for the ground water monitoring was the willingness of the land owner and/or operator to cooperate in the monitoring study.

Design the Monitoring Well System

The most common sampling points for ground water are monitoring wells, which when installed, become fixed sampling points. The primary considerations in designing the monitoring wells are well placement, installation, and construction. Ground water monitoring is conducted to collect physically and chemically representative samples of the ground water of interest. If the monitoring wells are improperly placed, installed, or constructed, inaccurate interpretation of the water quality data can result.

Well **placement** is based on the following: the monitoring study design, the ground water flow direction, the location of known or suspected pollution sources, the monitoring

objectives, the site geology, and the parameters that will be analyzed. Well placement for an aquifer-wide or large area definition of water quality requires the placement of wells in the predominant representative sediments and land uses; consideration should also be given to potential stratification of contaminants (Kimball, 1988). Wells can be placed randomly or on a grid pattern, with wells installed equal distances apart throughout the aquifer. Sites where monitoring wells could be influenced by point sources of contamination should be avoided.

Well placement considerations for other statistical designs such as before and after, paired watershed, or upgradient/downgradient, are similar for each. Wells should be placed to monitor water quality changes along the ground water flow path. This requires a well or wells in the upgradient area to define the background water quality. The upgradient area may or may not be on the exact line of flow from the area where the land use change or practice will occur. The upgradient well should be in an area that will be unaffected by any land use change. Downgradient wells should be placed in areas to monitor the ground water affected by the changes in management practices. To measure water quality changes along the line of flow, wells can also be placed between the up- and down- gradient wells.

If the water bearing materials are heterogeneous, multiple wells may be placed in the different saturated geologic materials at the up-and down-gradient sites. These may help in detecting water quality differences due to geochemical processes or differences in geologic material. Also, if the saturated thickness of a water bearing formation is greater than 10 to 15 feet, nested wells may be used to determine water quality changes with depth.

Nested wells are multiple wells installed in the same location but at different depths. The shallowest well should be installed with the midpoint of the well screen at the water table. (If historic water levels are available, the top of the screen can be placed within one to two feet of the highest known water table elevation.) The deeper wells can be installed with the top of the well screen placed at or near the same depth as the screen bottom of the next shallowest

well (see Figure 3). Up to three or four wells can be nested, depending on the saturated thickness, the length of the well screens, and the extent to which contaminants stratify. Inflatable packers may be needed to prevent the vertical movement of water between the different screened intervals in nested wells are placed in the same borehole. Separate boreholes for each well in the nest is recommended, however, to ensure proper sealing of the borehole.

The geology of a site must be adequately defined before the final placement of wells is decided. This is particularly true with heterogeneous formations such as glacial sediments. Small, lens deposits with different permeability than the predominant material, such as a clay lens within a sand deposit, can alter the flow path of water and contaminants. Bedrock, fracture systems, and geologic structures such as folds or faults, can also require special well placement. Sara (1991) describes several situations where geologic variability can affect well placement.

The number of wells needed for a monitoring project or a monitoring site depends on the study design. In USDA-NRCS (in press), a method is presented which can be used to approximate the number of wells (or samples) needed to estimate the mean for a water quality parameter. This method considers the estimate of the population standard deviation and the allowable difference from the mean. This method could be used for monitoring the water quality of a homogeneous aquifer. However, in heterogeneous geology, the number of wells will vary from site to site. At least three wells producing water from the same segment of a formation are needed to estimate the ground water flow direction. To detect changes in water quality due to a land use management change, upgradient and downgradient wells in each of the water bearing formations of interest are needed. If the ground water flow direction varies through time, more wells will be needed to document the changes in water quality resulting from changes in land management. Also, if vertical gradients or contaminant stratifications

are evident at a site, nests of wells will be needed both upgradient and downgradient at the site along the ground water flow lines.

The **installation** of monitoring wells usually requires some type of drilling to construct a bore hole for the well casing. Some method of geologic sampling and logging, which describes the subsurface materials, usually is done during the drilling of the bore hole. The drilling and sampling methods chosen depend upon the geology, monitoring budget, and water quality parameters of concern. Augering, boring, rotary drilling, reverse circulation, percussion drilling, and others are all methods of creating a bore hole for the installation of well casing. Four basic types of geologic samples are bulk, representative, undisturbed, and composite samples, and there are several sampling devices available to collect those samples. Various drilling and sampling methods and advantages and disadvantages of each are discussed by Davis et al., (1991) in *Practical Handbook of Ground-Water Monitoring* and by Driscoll (1986) in *Groundwater and Wells* .

Well **construction** details include: the type and diameter of casing, the type and length of screens, type of casing joints, type and amount of gravel pack, and seals for the annulus. The type of casing, screen, and casing joints chosen depends on the parameters that will be analyzed in the water samples because these materials can change the chemistry of the water that enters the well. Four types of casing and screen materials available are polyvinyl chloride (PVC), stainless steel, trifluoroethylene (commonly called Teflon™), and fiberglass epoxy resin. PVC is the least expensive and has the greatest potential to chemically react with the water in the well; trifluoroethylene is the most expensive and has the least reactive potential. Fiberglass epoxy resin has a low potential for chemical reaction with water and is moderately priced. Stainless steel casing is moderately priced but is not as easy to handle as the other types of casing. Casing can be connected with threaded couplers, casing manufactured with flush joints, or glue. Glue, however, can interfere with the chemistry of the water samples and should not be used.

The length of screen depends on the type of sample needed. To obtain a discrete sample from a particular segment of the saturated material, a short (three to five feet) screen is adequate; for an integrated sample over a larger segment or the full saturated thickness, a longer screen (10 to 20 feet) can be used.

The main considerations in choosing the source and type of gravel pack are the grain size of the pack and the potential contaminants within the pack materials. Gravel pack for the screen should be a clean, washed pack of sufficient permeability to avoid limiting the hydraulic conductivity of the water producing formation. Bentonite and cement are two materials that can be used to seal the annulus between the well casing and the bore hole and above the well screen.

There are several excellent references on monitoring well construction. These include *Practical Handbook of Ground-Water Monitoring* (Nielsen and Schalla, 1991), *Groundwater and Wells* (Driscoll, 1986), and *A Guide to the Selection of Materials and Monitoring Well Construction and Ground-Water Sampling* (Barcelona et al., 1983).

The direction of ground water flow at the South Dakota RCWP field sites was determined using new wells constructed during the initial stage of the field studies. Once the flow direction was known, monitoring wells were installed on the upgradient and downgradient edges of the field sites. Additional wells were installed across the field to determine changes in water quality below the site where best management practices were applied. The ground water flow direction varied, so it was important that wells were installed across the site along different flow paths. Nested wells were installed to determine stratification of the contaminants and vertical hydraulic gradients and were screened: 1) across the water table, 2) in the intermediate segment of the saturated materials, and 3) in the deepest segment of the saturated materials. Three wells were installed if the saturated thickness was greater than 10 feet. Multiple wells were also installed at some field sites to monitor different geologic

materials. For example, both unweathered and weathered glacial till was monitored in the upgradient and downgradient direction. The number of wells ranged from eight wells on a 40-acre site to 20 wells on a 26-acre site.

The ground water monitoring in the South Dakota RCWP project was conducted with monitoring wells installed with hollow stem auger drilling of two different diameters. Hollow stem auger drilling was chosen for several reasons: the drill holes were shallow (less than 30 feet deep), no water foreign to the formation was introduced, nearly undisturbed samples of the subsurface material could be obtained, and monitoring wells could be installed through the auger. Geologic samples were collected with a split spoon sampler at 5-foot intervals.

Mud rotary and standard flight (solid stem) auger drilling was used for preliminary test hole drilling in the South Dakota RCWP. Some monitoring wells were also installed using these drilling methods. These drilling methods provided preliminary geologic information quickly at a reasonable cost.

Two-inch diameter schedule 80 PVC well casing and screens were used for the South Dakota RCWP project. The casing was low in cost and easy to handle. There were some questions on the interference of the casing with organic materials such as pesticides, which was a key sampling parameter in the project. Selected well sites, however, were also equipped with wells constructed of a more inert material (fiberglass epoxy resin) to verify the pesticide analyses. Where the native geologic materials did not collapse into the well bore to provide a natural gravel pack or were not suitable, sand and gravel from the same area were used. Powdered, granular, and pelletized bentonite were all used for sealing the borehole annulus above the screen, through the confining layers, and at the land surface. Pellets were used to fill the annulus below the water table, and granular bentonite was used to seal the annulus above the water table. Powdered bentonite was used to seal the top three to four feet of bore hole.

Steps in designing monitoring wells and some lessons learned in the South Dakota RCWP project are:

- **Considering the monitoring study design, determine approximate locations for monitoring wells.** Using background information and data collected during the initial field work, the ground water flow direction and the depth of the wells can be estimated. The need to nest wells can also be decided, depending on the geology of the site and the potential stratification of contaminants. Nitrate is a contaminant that tends to stratify. Of a total 3,092 water samples analyzed for nitrate as nitrogen in the South Dakota RCWP project, concentrations above five parts per million were found only at depths of less than 20 feet below the water table. Nitrate concentrations (as nitrogen) did not exceed 0.2 parts per million at depths greater than 30 feet below the water table (Figure 4).

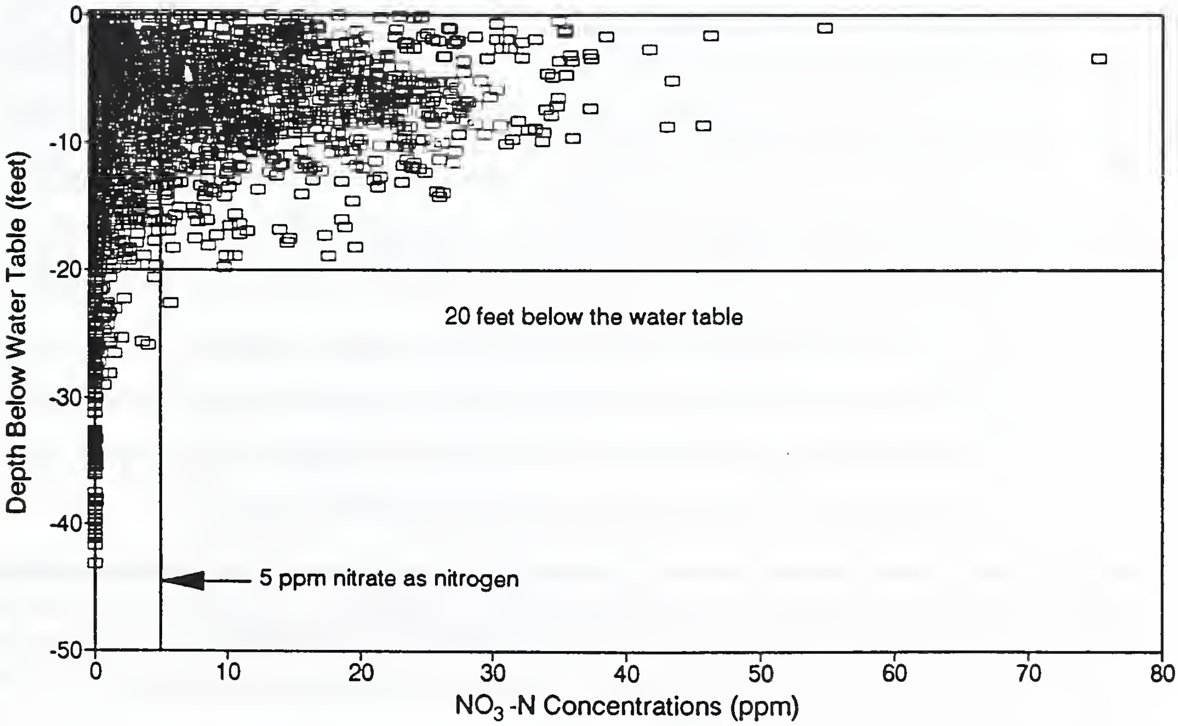

Figure 4. Nitrate concentrations versus feet below water table.

- **Estimate the number of wells needed based on the monitoring study design, the monitoring budget, and the site geology.**

- **When choosing well locations, consider the accessibility to the site for sampling equipment and personnel.**

KEY LESSON LEARNED: Even though road ditches and drainage ways may be more accessible for sampling of monitoring wells, they can act as recharge areas and may affect the quality of the water samples. Wells constructed in such areas may indicate either lower concentrations of parameters because of the increased dilution waters or higher concentrations because of runoff carrying high loads of agricultural chemicals.

- **Choose a drilling method that will provide the detail of geology needed, will reduce fluids introduced to the well bore, and will allow the installation of well casing to the desired sampling depth.** To verify gross differences in geologic formations such as glacial tills and sands, to determine depths to ground water, and to install wells to monitor water levels, rotary and standard flight auger can be used as quick and cost efficient drilling methods. A hollow stem auger can be used for the installation of monitoring wells in unconsolidated materials because: 1) it reduces the introduction of water into the well bore, 2) it allows split spoon sampling at frequent intervals, and 3) it allows the installation of monitoring wells at discreet depths. The hollow stem auger method was the most costly and the slowest used in the South Dakota RCWP project. However, the resources were well spent because of the data provided by the in situ sampling and discreet well placement.

KEY LESSON LEARNED: Spend the resources necessary for a good drilling program. The payoffs from using the appropriate drilling method include detailed geologic sampling, eliminating or reducing the introduction of water and contaminants to the well bore, and the correct placement of the well screen.

- **If the hollow stem auger method is chosen, select an inside auger diameter that will allow the placement of the casing and backfill materials inside the auger.** Two different diameters of hollow stem were used in the South Dakota RCWP project, 3 1/4 inch and 5 1/8 inch. The larger diameter allowed better well placement and provided greater integrity of the gravel pack and well seals. The larger diameter was more costly and slower, however.

- **Choose a casing material that will not interfere with the contaminants of concern.** PVC can be used for common nonpoint source pollutants such as nitrogen and common ions. PVC can cause bias or interference with organic contaminants. Most of the Oakwood Lakes-Poinsett RCWP monitoring wells were constructed of PVC; fiberglass epoxy-resin wells were constructed at several sites to verify the integrity of water samples collected for pesticide analysis.

KEY LESSON LEARNED: PVC casing is economical and serves the purpose of monitoring for nonpoint sources of pollution. Comparisons between water quality data from PVC and fiberglass epoxy-resin cased wells installed at the same monitoring sites at the same depth showed no significant differences in the sampling results for pesticides (Goodman et al., 1991).

- **Choose a casing and screen strength based on the depth of the well, the likelihood of materials collapsing around the screen in the bore hole, the type of grout used to seal the annular space, and the exposure to the elements.** Two-inch diameter Schedule 80 PVC casing was used in South Dakota because this casing material had been used in previous studies and had withstood the harsh climate of -30 to +100 degrees temperature extremes for over 20 years.

- **Choose the method to connect the sections of casing and screen.** Both threaded couplers and flush jointed casing were used in the RCWP project; the flush jointed casing is preferable because of the ease in making casing connections and the placement of the well casing through the hollow stem auger.

- **Choose the type and length of well screens.** Only manufactured screens should be used; hand-perforating pipe to use as well screens creates a fresh surface that can be chemically reactive. The slots of manufactured screens are more uniform which results in better well development and less turbid water samples. Manufactured PVC screens in 5-foot and 3-foot lengths were used in the RCWP project because discrete samples were needed.

- **Choose a diameter of well casing that is appropriate for the sampling techniques planned for the site.** Sufficient size is needed to allow sampling equipment into the well, to yield adequate amounts of water for samples, yet does not require excess effort in evacuating the water from the well before sampling. Two-inch diameter wells were used in the South Dakota RCWP project. Evacuation was relatively easy, and the diameter was adequate to allow the introduction of the sampling equipment. Samples from discrete sections of the aquifer could be obtained. If slowly recharging wells are anticipated, such as wells constructed in low permeability material, larger casing diameters may be beneficial for sampling efficiency. If the budget allows dedicated sampling equipment for each well, 4-inch diameter casing may be more convenient for sampling, although a more discrete portion of the formation is sampled with a smaller diameter casing.

- **Choose the source and grain size for gravel packing the annulus around the screen.** Washed, sterilized, and sacked gravel pack is available and will protect the integrity of water samples because it will eliminate the introduction of contaminants from a gravel pack.

- **If security for the monitoring wells is a concern, the wells can be secured with locked, metal well protectors to prevent vandalism (Figure 5).**

Figure 5. Metal, locked monitoring well protector.

Select the Parameters to be Measured

Physical and chemical measurements are needed in a ground water study. These measurements are made both in the field and in the laboratory. Physical parameters include measurements such as water level elevations and precipitation, water characteristics such as specific conductivity, and aquifer characteristics such as hydraulic conductivity. These are

needed to estimate how and where the ground water flows at a monitoring site. Most of the physical measurements are done in the field.

Chemical parameters include chloride, nitrate, pH, and many others. Some of these measurements are made in the field, but the majority are done in the laboratory. These are needed to define the quality of the water, both the natural chemistry and the chemical changes due to pollution.

When choosing the parameters to be measured in a project, the use of each measurement and how that parameter is going to be evaluated and reported should be considered. If parameters will not be used in the final evaluation, analysis costs would be wasted. As described in USDA-NRCS (in press), there are several factors that determine what variables could be measured. Considerations for selecting parameters to measure are: project objectives, type of water resources, designated use of the water resource, potential or actual pollution sources, difficulty or costs of certain analyses, and water quality problems. The reader is referred to Tables 4-1 through 4-8 in USDA-NCRS (in press) for suggested parameters for each of the above factors.

Several parameters such as some common ions, metals, and nutrients can be analyzed to define the general background quality of ground water. To detect the occurrence of contamination, parameters that suggest a particular pollution source should be analyzed. For example, nutrients would be analyzed in water where livestock waste is suspected as a contaminant source. If a contaminant and source have already been identified, that contaminant would be measured to find out if the application of best management practices improves the water quality. Some associated parameters may also be measured. For example, water contaminated with animal waste may also have increased total dissolved solids, sulfates, and chlorides; these parameters would be useful in evaluating the success of improved animal waste management.

The South Dakota RCWP project focused on improved nutrient and pesticide management and the effects of those practices on ground water quality. Because the use of ground water for drinking was impaired by nitrate contamination, the nitrogen species were included as parameters to measure. Ground water samples were also analyzed for pesticides commonly used in the area. There were many pesticides in use, but the analysis for these products consisted of a scan for several chemicals that were chemically similar. The cost for individually analyzing each chemical would have been prohibitive.

Several parameters such as chloride, electrical conductivity, dissolved oxygen, and total dissolved phosphorus, which may show degradation of the ground water from commercial fertilizer use, were also measured. Water level elevations were always measured before wells were sampled; hydraulic conductivities and measuring point elevations were measured once after the monitoring wells were installed. The amount of precipitation was not measured at the field sites; precipitation data from nearby National Weather Service stations were used.

Steps in compiling the list of parameters to be measured in a nonpoint source monitoring project and some lessons learned in the South Dakota RCWP project are:

- **Identify all parameters that will be measured.** Include all the physical, chemical, and biological parameters that will be needed to meet the objectives of the study.

- **Identify the field and laboratory methods for each parameter that will be measured.**

- **As the project progresses and periodic data evaluation is completed, reevaluate the list of parameters measured.** Parameters that had good correlation (sulfate, total dissolved solids, and specific conductance) were not

all needed for final data evaluation in the South Dakota RCWP project. Some of these parameters could have been eliminated from the chemical analysis. Some parameters may also be added if a need is shown. Precipitation was not measured at each field site in the South Dakota project, but final data evaluation illustrated the need for more site-specific precipitation data.

KEY LESSON LEARNED: Precipitation should be measured at each monitoring site. Precipitation data from nearby National Weather Service stations were used in data evaluation in the South Dakota RCWP. The data were inadequate because of the very localized, intense thunderstorms experienced in the area. Some areas within the project area experienced several inches of rain in a short time period. These rainstorms were not always recorded at the Weather Service stations.

Choose Sampling Methods and Equipment

The objective of sampling ground water is to obtain a representative sample of the water of interest to the study; therefore, the sampling equipment that will have the least chemical and physical effect on the sample should be chosen. Several criteria help decide what sampling equipment to use: the parameters to be analyzed, the potential effects of the equipment's construction material, the potential effects of the water delivery, the diameter of the well to accept the sampling equipment, the physical access to the well, the ease of equipment decontamination, and the operation of the equipment in extreme weather conditions.

There are many ground water sampling devices available, even for smaller diameter wells. Herzog et al., (1991) discuss the advantages and disadvantages of various ground water sampling devices including bailers, syringe devices, suction-lift pumps, bladder pumps and submersible pumps.

Dedicated sampling equipment for each well will reduce the potential for cross-contamination of samples between wells. Separate wells for in situ measurements from the wells used for sampling can also be considered for the same reason. These two alternatives, however, can be costly, and should be considered only when the parameters of interest and the sensitivity of the data require the additional efforts.

A variety of ground water sampling equipment was used in the South Dakota RCWP project to accommodate a range of physical and hydrologic conditions at the monitoring sites. Bailers, a peristaltic pump, and a bladder pump (Figure 6) were all used successfully. An air compressor was used as a power source for the bladder pump and to develop the monitoring wells after installation. The bailers and bladder pump were used to evacuate the monitoring wells before sampling and to obtain a sample for water quality analysis. The peristaltic pump was used infrequently to obtain water samples from monitoring wells that would not allow the other sampling devices to the depth needed for sampling. The peristaltic pump was used most frequently to filter water samples in the field when required. (Water samples were always filtered under pressure rather than suction to prevent degassing of the sample and

Figure 6. Bladder pump with trifluoroethylene tubing.

precipitation of metals that were being analyzed.) A field vehicle dedicated to the project was needed because of the amount of equipment used.

Both PVC and trifluoroethylene bailers were used to collect samples for nitrate and pesticide analyses, respectively. Meters to measure dissolved oxygen, electrical conductivity, pH, and temperature were used with verification of the measurements made in the laboratory. A weighted tape with a popper was used to measure water levels in each monitoring well before each well was purged and sampled. The popper was a metal cylinder approximately two inches in length with a concave bottom (Figure 7). The water level was measured when the popper hit the water and a distinct "pop" was heard.

The measurements of hydraulic conductivities required the development of special equipment because some monitoring wells recharged very rapidly. The rapid recharge did not allow the collection of the required number of measurements with conventional equipment (Kimball, 1988).

Considerations for choosing ground water sampling equipment and some lessons learned from the South Dakota RCWP project are:

Figure 7. Fiberglass tape with a popper.

- **Choose a sampling device(s) that can be lowered into the smallest diameter well casing used in the project.** Consider that all wells may not be plumb

and may not allow a sampling device to be lowered to the intended sampling depth. The South Dakota RCWP project had some wells that would not allow the bladder pump to be lowered. A short PVC bailer or the peristaltic pump had to be used to sample those wells.

- **Choose a sampling device(s) that will not chemically alter the sample during the delivery of the sample to the sample container.** There are three considerations: 1) the sorption and leaching potential of the device's construction material; 2) the pressure, temperature, or other changes that would change the pH or oxidation/reduction potential of the water; and 3) the potential of degassing of the water. A bladder pump with trifluoroethylene tubing and a silicon bladder was used successfully to prevent the above in the South Dakota RCWP project (Figure 6); it delivered samples that were in contact only with inert materials at low flow rates and positive pressures which minimized degassing and pH/oxidation-reduction changes.

- **Choose a sampling device(s) that is as portable as monitoring wells are accessible.** Some field conditions may require the use of samplers that can be easily carried long distances. In the South Dakota RCWP project, many well nests were located in the middle of cropped fields (corn). Driving the dedicated sampling van to the well sites was not possible, so lightweight bailers were used. The bailers, decontamination equipment, sample containers, and log books could be carried easily to the well sites in a backpack.

- **Choose a sampling device(s) that can be easily maintained and decontaminated and will operate effectively in extreme climate conditions.** The fewer parts to maintain and clean, the easier and cheaper the upkeep is, and the less likely it is for a "dirty" sample to be collected. Also, devices with

electronics and moving parts may freeze and break during winter sampling. The bailers worked the best in the South Dakota project during the winter and were easily decontaminated.

- **Choose a sampling device(s) that can lift the water from the sampling depth to the land surface.** A peristaltic pump can only lift water approximately 25 feet, but can be used efficiently for shallower wells.

- **Choose a sampling device(s) that can be operated and maintained by field personnel with relative ease.** In the Oakwood Lakes - Poinsett RCWP project, the bladder pump was easy to use and was very efficient but required extensive maintenance over time. Often, the maintenance could not be performed in the field. The pump had to be returned to the manufacturer for repair, causing delays in sampling. Arrangements to use a second pump were made during long repair periods for the original pump.

- **Choose a sampling device(s) that can produce a sample comparable to the recharge rate of the well.** The bladder pump worked the best in most situations in the South Dakota RCWP project. However, several monitoring wells were constructed in low permeability glacial till; the wells did not recharge quickly enough for the pumping rate of the bladder pump. These wells had to be bailed.

Determine the Sampling Frequency

The frequency at which samples are collected will vary according to project objectives, the hydrogeology of the sites (frequency of recharge and flow rate), the anticipated variability in

the data, and the project budget. The frequency may also be adjusted as interim data evaluation proceeds.

Frequencies for ground water sampling are usually a periodic sampling frequency such as quarterly and/or a recharge event-based frequency. The latter is far less common than the former because recharge events are usually not very well defined. Sampling recharge events can also require equipment normally used in surface water monitoring such as automatic samplers. Also, depending upon the extent of aquifer response, the recharge event may go undetected. Less frequent monitoring is required for long term, general assessment or trend monitoring. More frequent monitoring may be required for research or determination of cause and effect monitoring.

The monitoring frequency in the South Dakota Oakwood Lakes-Poinsett RCWP project varied, but began at quarterly intervals for all wells and monthly for a few selected wells. After the first five years of monitoring, this frequency changed to every two months for all wells and every two weeks for selected wells. The changes were made because interim data evaluation suggested the sampling may be missing peak concentrations of nitrate.

During the final evaluation of the soil profile and vadose monitoring data, it was theorized there were specific contaminant recharge events for both pesticides and nitrogen. These recharge events occurred quickly, and concentrations peaked, diluted, and returned to normal in varying sequences and times. One well nest was equipped with automatic samplers to determine the occurrence of recharge events. Monitoring data showed that runoff ponding near the well nest resulted in a recharge to the ground water system. Pesticide detections in the ground water increased following the recharge followed by a lack of detections in the well water.

KEY LESSON LEARNED: Ground water sampling frequency of at least twice a month or weekly for pesticide analysis and every two months for nitrate analysis is necessary to detect leaching events in South Dakota. A less frequent sampling schedule may be appropriate in the winter months and for various project objectives.

MONITORING SYSTEM IMPLEMENTATION

Implementation includes many activities to install the monitoring system and collect water samples and other measurements. These include: negotiating contracts for laboratory, drilling, and other work; writing standard operating procedures; training sampling personnel; purchasing sampling equipment; drilling, installing, developing, and surveying monitoring wells; collecting water samples and other measurements; and reevaluating the components of the monitoring study design as the project progresses.

If drilling and laboratory capabilities are not available within the agency or group responsible for monitoring, contracts may be negotiated to accomplish that work. The contracts should include schedules for work completion, costs, acceptable methods, quality assurance/quality control requirements, and other expectations of the monitoring agency.

As part of the project quality assurance development, standard operating procedures should be written for drilling, well installation and development, well sampling, and other processes as needed. The standard operating procedures should be used to train field personnel to reduce human error and the introduction of biases in the data. The procedures should be easy to follow, easily understood, and followed completely during each sampling or other event. **The documentation of and adherence to the sampling procedures, and training in the procedures cannot be overemphasized.**

There are many variations of ground water sampling procedures that depend on the monitoring objectives and parameters of interest. The sampling procedures should include the following:

- preparations prior to sampling trips
- equipment and methods for purging and sampling the wells
- methods and equipment for measuring field parameters
- field books and field documentation requirements
- quality assurance and quality control methods and sample requirements
- sample preparation and/or preservation methods
- sample handling and transport requirements
- chain of custody requirements.

After the drilling is complete and the monitoring wells are installed, each well should be developed by agitating the water column in the well and then removing the water. Well development cleans and sorts the gravel pack and cleans the well casing to reduce the turbidity in the water samples collected from the well. Kraemer et al., (1991) discuss several methods for developing monitoring wells. Ground water sampling and other measurements in the wells can begin after the wells have recovered from development. Also, the elevation and location of each well should be surveyed so ground water level elevations and flow direction can be determined.

Most of the drilling for the Oakwood Lakes-Poinsett RCWP project was completed with state owned rigs, so contracts were not necessary for the state agency responsible for monitoring. Project hydrogeologists supervised the drilling and well installation, and performed the well development. Surveying was also conducted by agency personnel.

Laboratory contracts for the life of the project were negotiated successfully with two laboratories. One laboratory performed all the pesticide analyses, and the second laboratory analyzed water samples for all other constituents. The laboratory contracts included: the number and frequency of samples anticipated, the times for delivery of samples to the laboratory, the analytical methods to be used, the detection limits required for each parameter, the quality assurance and quality control requirements, and the cost associated with each analysis.

Standard operating procedures for the South Dakota RCWP project were prepared as part of the project's quality assurance/quality control document. These written procedures were used to train all personnel involved with sample collection. An advantage to the sampling program in the South Dakota project was little turnover in sampling staff; the water quality sampling was conducted by only a few people. Besides the standard operating procedures, a sampling book was carried in the field by sampling personnel. The sampling book contained the following: maps of each monitoring site, the drilling log for each well, well construction details, the recharge capabilities of each well, the sampling device recommended for each well, and an equation to determine the volume of water to be purged from each well, depending upon the measured water level.

Steps in implementing the monitoring system and some lessons learned in the South Dakota RCWP project are:

- **Depending upon the number and frequency of samples to be analyzed by the laboratory, enter into a contract with the laboratory.**

- **Prepare standard operating procedures for well installation, construction, and development, sample collection, and other measurements.**

- **Purchase the equipment necessary to collect water samples and other measurements.**

- **Train all sampling personnel in the procedures and requirements for sampling.**

- **Prepare a pre-sampling check list to ensure all equipment and supplies are taken to the field.** The check list should include answers to the following questions:

  What are the right number and type of sampling containers?
  What meters are needed?
  Is there a sufficient amount of decontamination water and preservatives?
  What sampling devices are needed and are they operational?

- **Drill the boreholes and install monitoring wells.** Consider the following when drilling and installing monitoring wells:

  - **If hollow stem auger drilling is used, it may be necessary to use a plug to keep material from entering the auger during drilling.** The drilling for the South Dakota RCWP project was often in saturated fine to medium sands, and a differential head sometimes developed between the inside and outside of the drill stem. When the drill plug was pulled so a geologic sample could be taken or a well installed, sand was carried into the drill stem. The sand obstructing the drill stem was washed out with water.

  - **Take precautions in extracting the auger when installing a monitoring well to allow for consistent collapsing of the saturated**

material around the well screen. When the drill stem is pulled after the well casing has been installed, differential collapsing of the subsurface materials can cause a curvature of the well casing. This prohibits the lowering of sampling equipment in some wells. Centralizers, or guides used to center the casing in the borehole, can also reduce well curvature.

- **Place the well screen at a depth and of sufficient length to yield water samples to meet the project objectives.** For example, to monitor contaminant inputs from the surface to the water table, the well screen should be placed to intercept the water table and account for extreme fluctuations of the water table. Most nonpoint source pollution projects will be evaluating changes in land use at the land surface; therefore, shallow water table wells will be the most common well depth.

- **Carefully place the gravel pack to ensure it surrounds, covers, and extends to a few inches to a foot above the top of the screen.** If the pack is emplaced too quickly, bridging of the pack in the borehole may occur.

- **To ensure the screen receives only water from the formation or interval of interest, bentonite or a cement grout should be used to seal the annulus above the gravel pack.** Two intervals of the annulus should be sealed in a shallow, water table well - the three to four feet above the gravel pack and the top three to four feet of the borehole. Sealing the well bore is especially important in a nest of wells and where wells are screened below the water table.

- **Use care in placing the seals in the borehole to avoid bridging of the sealing material.** This is essential for wells completed below a confining layer. Bentonite pellets and granular bentonite were successfully used with the large diameter hollow stem auger in the RCWP project. A bentonite slurry emplaced through a narrow tube (drop pipe) worked the best. Powdered and granular bentonite was used successfully in unsaturated conditions.

Figure 8. Bentonite seal at the land surface.

- **In wells completed in saturated unconsolidated sand and gravel, the sides of the borehole will likely collapse when the drill stem is pulled out of the ground, making the emplacement of a seal above the screen difficult.** The well is still usable if the well does not extend too deep below the water table, because the well will not be pumped at high rates. However, a seal should be placed from the land surface down to a three to four foot depth to prevent runoff from the surface into the well bore (Figure 8).

- **Document the drilling and installation process by recording the geologic log and the construction details of each well.**

- **Develop the monitoring well after installation by over pumping, surging in the well screen with a surge block, or air or water jetting within the screen.** The monitoring wells installed for the South Dakota RCWP project were all developed using one or a combination of the above methods.

- **Survey each monitoring site to determine location and elevations of monitoring points.**

- **Determine the hydraulic conductivity at each site or at multiple points within a site.** Single-well baildown or slug testing was preferred over a site pump test in the Oakwood Lakes-Poinsett project. This was because the distribution of hydraulic conductivities over a site and vertically within the geologic materials was quite variable and was important in evaluating and predicting contaminant pathways. Pressure transducers and data loggers were needed to measure hydraulic conductivities in rapidly recharging wells.

- **Initiate the collection of water samples.**

- **Measure and record the water level in each well before removing any water from the well.**

- **Purge wells to remove the stagnant water and to collect a water sample that represents the formation water.** There are several theories on the appropriate amount of water to purge before sampling (Herzog et al., 1991). In the South Dakota project, low recharging wells were purged using a bailer

until the well was bailed dry. In quickly recharging wells, the bladder pump was used to purge the well until pH, temperature, and electrical conductivity stabilized.

- **After collecting the appropriate amount of water for the sample, measure the field parameters such as dissolved oxygen, specific conductance, pH, and temperature if the measurements were not taken as part of the purging process.**

- **If the analytical technique for the parameter of interest requires filtration, field filter the sample following extraction of the sample from the well.**

- **Properly preserve and prepare each sample for shipping according the appropriate analytical technique that will be used.** For a complete listing of parameters, sample preservatives, maximum holding times, and the appropriate sampling container, the reader is referred to the US Environmental Protection Agency "Handbook for Sampling and Sample Preservation of Water and Wastewater," (US EPA, 1982).

- **Establish the appropriate sample collection method for each well, i.e., flow rate, volume of bailer, etc.** A field notebook containing all the pertinent information for each sampling site was used in the South Dakota project. The notebook included the sampling device recommended for each well, the recovery rate of the well, and the volume of water to evacuate from the well before sampling.

- **Ensure field personnel document field procedures and conditions such as the weather, any anomalies at the site, and any problems in sampling; any**

other pertinent data, including well development, repair, and maintenance, which could be used to help in the evaluation of the data or to explain data anomalies, should also be documented.

- **As the project progresses and data are periodically evaluated, reevaluate the components of the monitoring study design and make appropriate changes necessary to meet the monitoring objectives.**

GROUND WATER DATA MANAGEMENT AND EVALUATION

Data evaluation provides the fundamental means of correlating water quality analyses with other information including hydrology, geology, and soils data. The process of data management and types of data evaluation techniques must be considered during the early planning stages of monitoring study design. This ensures the data and equipment necessary for various methods of evaluation are available. The data evaluation techniques are chosen based on the monitoring study design and monitoring objectives.

Water quality monitoring projects may result in large volumes of data. A practical means of entering, storing, and manipulating the data is essential. Computer data bases and the direct entry of laboratory data reduce data recording errors. Data management processes, including data entry, verification, and use should be part of the standard operating procedures developed for the monitoring project.

Data analysis is an ongoing activity, not just a post-monitoring effort. Periodic analysis provides a basis for modifying monitoring techniques and project activities. This may result in a higher probability in accomplishing project objectives and may make better use of available funds.

Data analysis techniques can be simple or complex. Visual representations of the data, simple statistical descriptions, statistical testing, and complex computer modeling can be used to provide evaluations of the data for reporting. Visual representations include tables, graphs, maps, cross sections, concentration isopleths, and others. "Looking" at the data can reveal obvious trends or characteristics; it can also help to raise questions for further statistical testing.

Simple statistical descriptions include the mean or median and variability of parameter concentrations. These descriptors can be combined with visual representations to examine areas for further statistical testing or investigation. One example is a time series graph to show the change in median concentrations of nitrate over time in a well. This may help lead to testing whether nitrate concentrations in ground water were significantly different after fertilizer management was used near the well. Further statistical evaluation of the data may be necessary to correlate nitrate concentrations in ground water to the use of fertilizer management. **Project Evaluation** on page 59 describes various evaluation techniques for different monitoring designs and water quality objectives.

Computer modeling is a tool that can be used to predict possible outcomes of land treatment techniques. Ground water flow and fate and transport models can be used to hydrologically describe an area and how the system may respond to changes in contaminant loadings. Models are only predictive and should be used with caution.

In the South Dakota RCWP project, time versus concentrations of certain parameters, frequencies of pesticide detections, and concentrations of nitrate versus depth below water table were plotted to detect any obvious trends or unique phenomena in the data (Figure 4). Geologic cross sections, fence diagrams, ground water flow maps, and site maps were used to visually present project data.

Nitrate data were tested for normality and were found non-normally distributed. Since the data were not normally distributed, non-parametric statistics were used to evaluate whether changes in ground water quality had occurred due to the application of best management practices. Median concentrations of certain parameters rather than mean concentrations were used to compare data. Medians were used because they are more of a measure of central tendency than means in non-normally distributed data (Crawford, 1984).

Pesticides were detected at extremely low (in fractions of a part per billion) concentrations, if detected; therefore, the temporal and spatial distributions of the number of detections were evaluated rather than trends or changes in concentrations. Any further analysis was difficult because 85% of the detections were a one time event. Sara and Gibbons (1991) discuss possible evaluation methods for data with a high number of nondetections.

Ground water quality data were aggregated by site, site-type, best management practice, year, and geology for comparisons. A unique classification system of "geozones" was used to aggregate ground water quality data and reduce the variability of the data. This was necessary because of the heterogeneous hydrogeologic systems at the monitoring sites. Figure 9 illustrates the geozone abbreviations displayed on a diagrammatic cross section. The schematic cross section is not specific for a single site but represents a composite of the stratigraphic sequences found throughout the project area. Water quality data from monitoring wells completed in similar hydrogeologic systems were aggregated and compared.

The Mann Whitney U or Wilcoxan 2 sample test (SAS Institute, 1985) were used to test for statistically significant differences in median nitrate concentrations between monitoring sites within geozones. Differences between geozones using water quality data from several sites were also tested. Cluster analysis and analysis of variance were used but were less useful than other analyses; the cluster analysis was very labor intensive. These parametric tests were also less appropriate because of the normality (or lack of) of the data (SAS Institute, 1985).

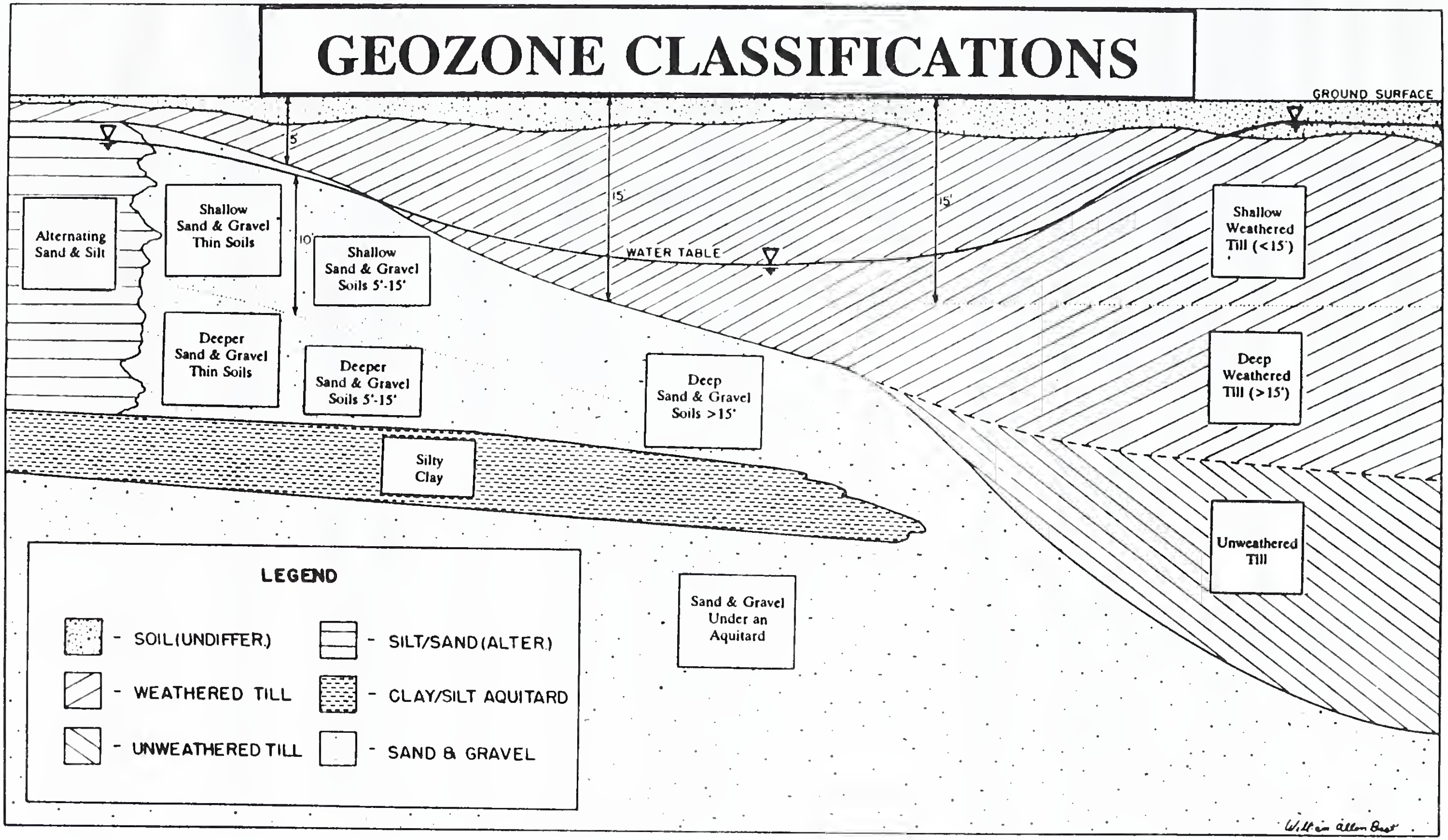

Figure 9. Schematic cross section illustrating geozones (not an actual geologic cross section but a composite of all sites).

Pre- versus post- best management practice implementation analysis was not possible in the South Dakota RCWP project; two control sites, one that was not farmed and one that was farmed without best management practices, were used to compare farmed versus unfarmed conditions and best management practices versus no best management practices. The differences in management practices between the farmed sites with and without best management practices were small, resulting in no significant differences in water quality. To determine the relationships of management practices to water quality, exaggerated differences in the management practices are recommended. Various monitoring strategies that include monitoring before and after best management practice implementation are recommended instead of control site monitoring.

Steps to manage and evaluate data and some lessons learned in the South Dakota RCWP project are:

- **Purchase the computer equipment and software necessary to store, manage, and manipulate the data.**
- **Develop the data bases necessary to store and manage project data.**
- **Enter and proof data as they become available.**
- **As data become available, visually present the data to detect any obvious trends or to choose further evaluation methods.**
- **Test the data for basic assumptions necessary for statistical testing.**
- **Use several data evaluation techniques to explore various possibilities in the data.**

- **Reevaluate monitoring design and objectives to ensure the monitoring is meeting project objectives.**

KEY LESSON LEARNED: Shallow ground water quality appeared to change more rapidly than originally anticipated in the project. It was initially anticipated that changes could be seen in five to six years, but the data indicated there was a potential for changes to occur in a much shorter time period. Changes were sometimes seen in hours or days following a precipitation event. Data evaluation early and periodically during the project lead the monitoring team to increase the frequency of sampling because of the quick responding hydrologic system.

NEW DEVELOPMENTS

The most significant development in ground water monitoring in terms of cost and time savings has been the **immunoassay analytical technique** for pesticides. This is an analysis that can be performed in the field, is quick, and inexpensive because several water samples can be analyzed in a short time. The immunoassay technique is product-specific, that is, it will result in measurements of one chemical or group of chemicals. For example, an atrazine immunoassay will indicate detections of atrazine and other triazines. There are, however, several product-specific kits currently available.

The immunoassays may be useful in nonpoint source pollution monitoring studies if the chemicals previously and currently used on a site or in an area are known. To determine the presence of any pesticide in the ground water or to meet certain regulatory compliance requirements, however, laboratory methods that will "scan" for various chemical compounds or have a lower detection limit are needed to first characterize the ground water.

Another development in sampling is the availability of reasonably priced **dedicated sampling devices**. Submersible pumps and bailers are available in various diameters and lengths.

Submersible pumps can be manufactured to the monitoring well specifications and equipped to fit into and connect to the well. When the well is sampled, an outside power source is connected to the pump and the dedicated discharge line is connected to produce the water sample.

Dedicating samplers to a well/site/project reduces the occurrence of potential contaminant carry-over from well to well or site to site. Dedicated samplers will add to the credibility of the sampling results. This method of sampling also reduces the time of sampling because de-contamination is usually not necessary.

Global Positioning Systems (GPS) is a system of orbiting satellites for a variety of U.S. military and national defense purposes. Field instruments and land base stations together pick up directional data emitted by the satellites to determine the latitude, longitude, and altitude of any location in the world. The accuracy of the data varies and increases with the cost of the field equipment. The GPS can be used to determine locations of potential pollution sources, water resource boundaries, monitoring stations, land treatment practices, and anything else where locational data may be needed for project evaluation.

Ground water contamination assessments and cleanups in recent years at point source releases and discharges, particularly from leaking underground storage tank facilities, have resulted in the development of **improved drilling, well construction, and sampling techniques**. There are several references available describing these techniques, but the most up-do-date information may be found in professional organization publications.

GROUND WATER/SURFACE WATER INTERACTION MONITORING

INTRODUCTION

Monitoring surface water/ground water interactions can be divided into two areas that meet different needs. **Monitoring surface water recharge to ground water** may be useful to determine the impact of surface water on a ground water resource. This should be the focus of monitoring if the goal is to document contaminant movement from the land surface to the aquifer. This can be done in conjunction with vadose zone monitoring and ground water monitoring. **Monitoring discharge of ground water to a lake or stream** should be the focus of the monitoring plan if ground water comprises a significant portion of the water or contaminant budget of the surface water body. The type of monitoring needed will vary depending on the goals of the project and the nature of the water quality problem.

The following discussion will focus primarily on monitoring ground water discharge to a lake. Experiences of the South Dakota RCWP project will be used to illustrate how monitoring of these interactions can be used. Monitoring techniques discussed in the **GROUND WATER MONITORING** and **VADOSE ZONE MONITORING** sections of this document are pertinent to studies of ground water recharge. This section will be limited to monitoring movement of water from ground water systems to surface water systems.

PRE-PROJECT PLANNING AND MONITORING SYSTEM DESIGN

Planning is necessary before monitoring can begin. It will help ensure that a study design and instrumentation are selected that will result in completion of the monitoring objectives. Pre-project planning should include the following steps: **1) review existing data, 2) choose a monitoring study design, 3) choose methods, 4) choose monitoring sites, 5) select parameters to be analyzed, 6) choose sampling methods and equipment, 7) determine**

sampling frequency, 8) develop field and lab quality assurance/quality control methods, 9) establish data handling and storage procedures, 10) choose data evaluation procedures, and 11) identify reporting needs. A budget can be developed and a report format constructed after the above components have been established. A complete monitoring plan for surface water/ground water interactions should include a description of all of these choices in terms of how they meet the monitoring objectives.

Important considerations as the monitoring plan is developed include:

- **Outside review of the monitoring plan is recommended.** Obtaining the opinions of others will help to determine if the plan is likely to meet the monitoring objectives. This may be a painful experience but outside comment will likely improve the plan.

- **Include monitoring elements in the plan only if needed to meet the objectives of the project.** Resources can be easily diverted to lines of investigation that are of interest to principal investigators that do not fit the project objectives.

Review Existing Data

To help characterize the system, **existing data for the project area should be reviewed.** Previous studies may have produced data related to the water quality, geology and hydrology of surface and ground water resources in the project area. The review of existing data should be conducted by an interdisciplinary group familiar with the project area. For example, a hydrogeologist might be best able to review existing data and determine whether ground water is a major contributor of water or nutrients to a lake or stream. A limnologist may be needed to determine the impact on the receiving lake. Other disciplines may be needed depending on the nature of the receiving water body. Refer to the **GROUND WATER MONITORING** section of this guide for a list of potential data sources for ground water.

Data sources pertaining to surface water and the information provided are:

Table 1. Background data sources for surface water.

DATA SOURCES	INFORMATION PROVIDED	WHERE TO FIND
Lake Assessment Reports	Watershed size, trophic state, water quality, and maps	State Natural Resource or Water Quality Agency
305b reports to congress	Beneficial uses and threats to the use of rivers and lakes	State Natural Resource or Water Quality Agency
EPA Eutrophication Study	Chemical and biological data on selected lakes	U. S. Environmental Protection Agency
Project Reports (208, 314, 319 studies)	Various water quality and land use data based on past water quality projects	State Library State Natural Resource or Water Quality Agencies
Thesis Projects	A wide range of topic specific information	University Libraries
EPA Storet Data Base	Water quality data and maps	U. S. Environmental Protection Agency
Geology and Hydrology Reports by County	Descriptions of the formation and hydrology of lakes. Major ions present	Federal and State Geological Survey Agencies
Water Resources Data Reports	Discharge and water quality of major rivers	U. S. Geological Survey

It is unusual to have enough existing data to adequately define the geology and hydrology of the study area and to select monitoring sites. It is likely that **additional data collection** may be necessary. This may include drilling test holes and collecting core samples of sediment in areas adjacent to the lake or river. This data will provide the information needed to evaluate potential sources of ground water supply or determine areas that are likely to be affected by ground water discharge. Water sampling to evaluate ground water quality may be needed to complete the monitoring system design.

The equipment needed and the steps to follow to collect additional geologic data and to determine the potential for ground water connections to the surface water body are similar to those described in the **GROUND WATER MONITORING** section. Methods to evaluate the potential for ground water discharge within a lake bed are discussed later in this section.

KEY LESSON LEARNED: Gather and use as much existing information as possible before designing a monitoring system. Collect additional data if the available data is inadequate to determine the importance of surface water/ground water interactions or is not detailed enough to choose potential monitoring sites.

Excess nutrient loadings were identified in a 208 Water Quality Study Area report as the major water quality problem for the lakes in the project area. Based on aquifer maps of the area, a hydrogeologist concluded the Oakwood Lakes were supplied, at least in part, by ground water. Monitoring at RCWP field sites adjacent to the lake indicated that shallow ground water contained elevated concentrations of nitrate as nitrogen (approximately 8 milligrams per liter) and phosphorus (approximately 0.035 milligrams per liter). A limnologist determined water from this source could constitute a hypereutrophic loading to the lake.

One of the monitoring objectives included development of water and nutrient budgets for the Oakwood Lakes System. Ground water discharge monitoring was included in the plan to determine, with direct measurements, the quantity and quality of ground water entering the Oakwood Lakes.

A sand and gravel isopach map (contour of the thickness of sand and gravel) was prepared from 55 test borings since the sand and gravel aquifer was expected to be the most prolific contributor of water to the lakes. The borings were advanced through both till and outwash to various depths. To include only that sand and gravel which were expected to impact the

Oakwood Lakes the following assumptions were made: 1) the lake elevation was 1625 feet above mean sea level, a level recorded in 1982; 2) the lake depth was 10 feet; and 3) up to 15 feet of aquifer beneath the bottom of the lake would be an important contributor to the lake. Therefore, the thickness of sand and gravel above an elevation of 1600 feet mean sea level was calculated from drill logs, plotted and contoured (Figure 10).

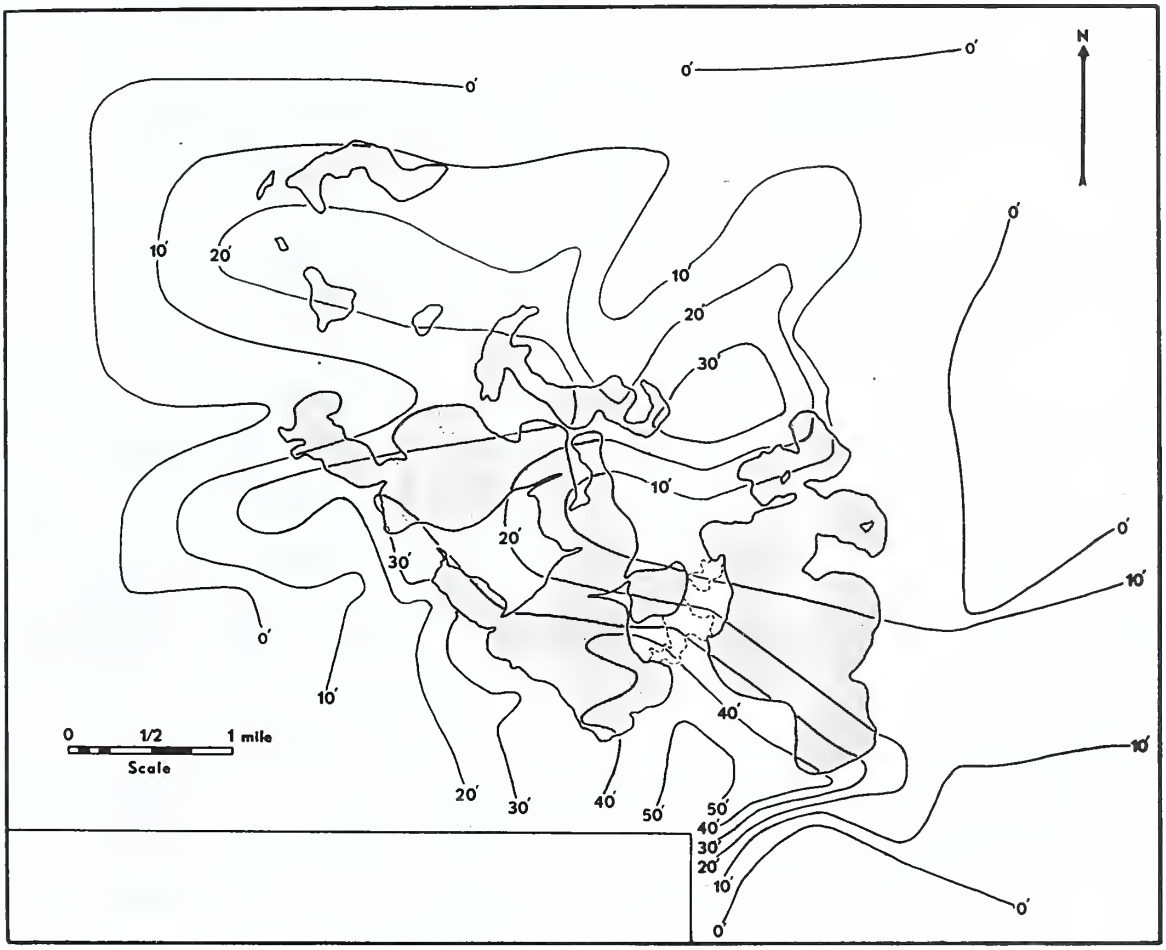

Figure 10 - Sand and gravel isopach map of the Oakwood Lakes area

Depth to water at the time of drilling from drill logs and water elevations from eight existing monitoring wells in the area were converted to approximate aquifer water elevations. These water table elevations combined with the sand and gravel isopach map were used to develop a

map which approximately delineated potential inflow, outflow and flow-through areas around the lake (Figure 11).

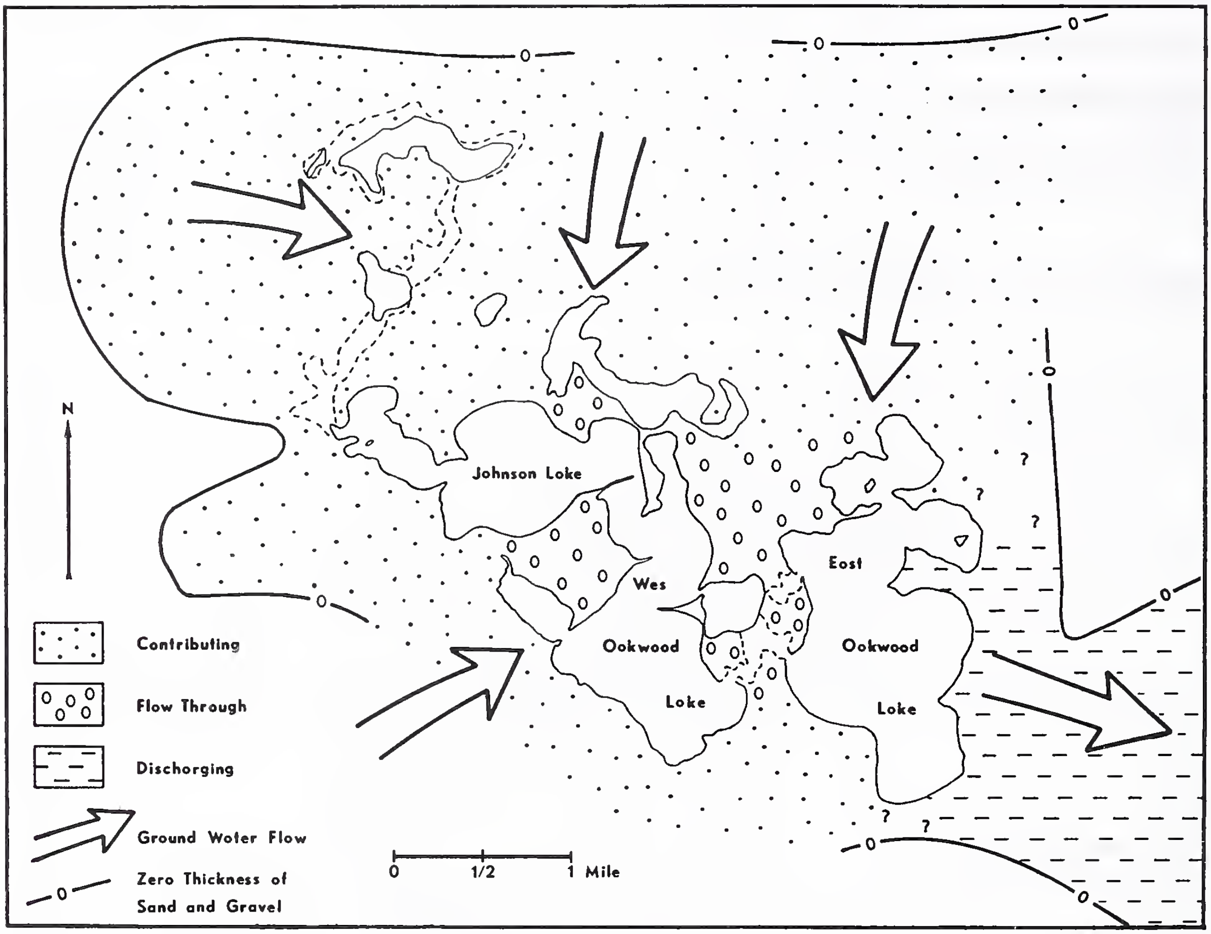

Figure 11. Potential inflow and outflow areas around the Oakwood Lakes

Considerations and steps to take in reviewing existing data include:

- **Organize a team of interdisciplinary professionals including hydrogeologists, limnologists, and chemists to review existing data and to plan, develop, and implement the monitoring system.**

- Obtain test borings of the area available from other agencies and geology resource investigations conducted by the state.

- Use water table information from the drilling logs to get an indication of flow direction. The data may be too coarse to allow the construction of a ground water contour map if the drilling occurred over a long period of time.

- Determine the areas (aquifers) that are likely contributors of ground water to the surface water body of interest.

- Determine the water quality, trophic state, and hydrology of the surface water body.

- Estimate the pollutant loadings that would constitute an unacceptable loading to the surface water body in order to maintain beneficial uses.

- Collect additional data as necessary to fill in gaps that may exist in the existing data.

- Construct a more detailed map showing the thickness of sand and gravel (isopach) in the area to determine key locations in the lake-ground water flow system.

- Prepare a ground water contour map to determine ground water flow direction.

- By combining the isopach and ground water flow direction map, prepare a "surface water/ground water interaction" map showing inflows, outflows, and flow- through areas.

Choose a Monitoring Study Design

As point sources of pollution are better controlled, it has been recognized that many remaining water quality problems are nonpoint source in nature. One of the largest unknowns in this diverse type of pollution is the discharge of ground water with dissolved pollutants to the lakes and rivers. Study designs useful for many nonpoint source projects were discussed in **NONPOINT SOURCE PROJECT ELEMENTS**. Most study designs presented are used to link land treatment with observed water quality changes (an important project objective). However, if the objective is to determine the relative contribution of ground water to the hydrologic and nutrient budget of a river or lake, "quantification" would be the appropriate study design. It is similar to methods used for gauging the flow of a river and collecting water quality samples used to determine pollutant loads which have been used on many surface water projects. By methods discussed in the next section, the quantity of ground water is measured and the concentration of various dissolved constituents are determined. A mass loading to or loss from the surface water body is calculated. Although these budgets may not be useful to directly evaluate a best management practice, they can be used to estimate the relative importance of pollutants from different water sources. If the source of water affected by the practice is of minor significance to the overall budget, little change in the water quality of the receiving body would be expected.

Select Methods for Measuring Ground Water/Surface Water Interactions

Several methods have been developed to estimate or measure ground water/surface water interaction. Some of these methods involve calculation or inferences based on indirect measurements and others are based on direct measurement. A review of several direct and indirect methods to establish waste load allocations from ground water discharge is contained in EPA (1991). Attempts have been made to directly measure movement of water between surface water and ground water systems with a variety of instruments since the 1940's

(Carr and Winter, 1980). One of the most commonly used instruments has been the Lee design seepage meter (Lee, 1977). The following is a brief description of several methods available. Before these methods are applied to a specific project, a thorough review of the literature is suggested.

Hydrologic Budget

This method is based on development of a hydrologic budget for a surface water body. All inputs to the system (streamflow, precipitation) and losses to the system (evaporation, outflow) and change in volume are calculated in an equation where:

$$\text{inflow} = \text{outflow} \;\; + \text{ or } - \;\; \text{change in volume}$$

The amount of water needed to balance the equation is attributed to gain or loss from ground water.

Advantages

This method is simple and does not require direct measurement of ground water. Many of the components needed may be available from hydrology studies. Others can be estimated based on published estimates of annual precipitation, runoff coefficients, lake level data, and evaporation rates.

Disadvantages

The traditional method of measuring ground water inflow to lakes by calculating the residual of a water balance study is unacceptable in many cases (Winter, 1981). Success of this method is limited by the ability to accurately measure precipitation, evaporation, and

streamflows. Accurate determination of evaporation from the lake surface and direct runoff to the lake from small channels is difficult.

Near Shore Ground Water Studies

Another common approach for obtaining estimates of ground water/surface water interaction is to install observation wells on land near the shore or in the water basin. The wells are then used to obtain measurements of the distribution of the hydraulic head and estimates of permeability. Darcy's Law is used to calculate ground water discharge using estimates of hydraulic conductivity and the cross sectional area of aquifer delivering water to the lake or river (Driscoll, 1986).

Advantages

Samples taken from land wells give a good indication of the quality of ground water that is flowing toward the surface water system. This allows loadings of nutrients and other solutes carried to the surface water system to be calculated separately from fluxes between the sediment interface and water within the surface water body.

The method is applicable to many locations. Existing wells and available drill logs can be used to estimate water level elevations and to estimate other parameters needed to calculate discharge using Darcy's Law. This method can be used to evaluate whether more direct methods to determine ground water discharge are needed (EPA, 1991).

Disadvantages

This method is often unsatisfactory because it is seldom feasible to estimate permeability by less than an order of magnitude and because surface water/ground water interaction is often

controlled at or near the sediment-water interface (Lee, 1977). Calculations assume that the aquifer material is homogenous and isotropic and of constant thickness. This may not be true. Due to the geologic forces that formed the surface water body, the cross section of the aquifer exposed to the surface water may not be the same as that found at the monitoring well locations (EPA, 1991).

Streamflow Gauging

In this method streamflow measurements along various segments are used to determine net gain or net loss along specific stream segments that can be attributed to ground water (Lee, 1988).

Advantages

Measuring flow along selected reaches of small streams is inexpensive. Segments can be selected that can be related to a specific land use (Lee, 1988).

Disadvantages

Estimates of ground water discharge and recharge is dependent on the ability to accurately measure streamflow in each stream segment. Good discharge measuring sites may not be available in the segment above and below the site under study. Intermittent flow and periods of low flow may be difficult to quantify.

Hydrograph Separation

Hydrograph separation can also be applied to stream gauging data. This method involves plotting the recession limb of a hydrograph for a specific storm event on semilog graph paper.

Changes in slope of the lines separate the hydrograph into segments used to estimate contributions to streamflow from runoff, interflow and ground water flow (EPA, 1991).

Advantages

Hydrograph separation is inexpensive, simple to apply and has been widely used by investigators throughout North American and the United Kingdom (EPA, 1991). It can also be used with tracer studies to estimate contaminant loading. Continuous stage or discharge data are readily available on many larger rivers and streams from the United States Geological Survey.

Disadvantages

Hydrograph separation assumes precipitation to be evenly distributed at the same intensity and duration (EPA, 1991). These conditions may be hard to meet, especially for large watersheds. Continuous records of discharge for small streams are generally not available. Setting up gauging stations and collecting discharge data increases the cost of this method.

Ground Water Modeling

This method is based on simulation of aquifer or watershed systems by describing parts of the system and processes within the system with mathematical equations. These equations are then solved to develop estimates of ground water discharge.

Advantages

Numerical models can be useful as a screening or predictive tool. Numerical models calibrated to simulate watersheds in different regions of the country can be used to assess the

general effect of various regulatory scenarios or land management scenarios on ground water quality in watersheds located in those regions (EPA, 1991). Solving for these "what if" situations can help assess the relative benefits of different management plans.

Disadvantages

Before a numerical model can be used for predictive purposes, a large amount of input data is often required to properly calibrate the model. The amount of data required will depend on the type of model used, the objectives of the study, and the level of accuracy required. Acquisition of the needed data can require considerable time, expertise, and expense. Because of these constraints, the numerical model may have limited usefulness in cases where data are scarce and funding is limited (EPA, 1991).

Geophysical Techniques

This technique is usually applied to large, deep water bodies. Shipboard geophysical systems are used to characterize bottom sediments along the ship's path. Hydraulic properties of the sediment are then used to calculate ground water discharge. Techniques include: seismic exploration, electrical charge of sediments and current decay, measuring resistivity of sediments, and measuring anomalies in temperature and bulk conductance of sediment (EPA, 1991). Temperature and conductivity probes can be dragged behind small boats on shallow water bodies to locate variations that can be used in potential upwelling areas for further study. Continuous contact with the sediment is important (Lee, 1985).

Advantages

Geophysical methods can be used to characterize bottom sediments over large areas of deep water bodies at less cost than direct measurement techniques (EPA, 1991). This technique can

be used for quick reconnaissance to help identify sites to locate instruments for direct measurement of seepage.

Disadvantages

Uncertainty of measuring sediment characteristics by these methods is greater than with direct measurement methods. If the assumptions made are not true, results will be questionable. Field verification of the results can be very difficult and expensive to obtain in deep water. These methods require a large boat or ship, depending on the water body, an array of instruments and support equipment, and personnel with considerable expertise (EPA, 1991).

Tracer and Isotope Studies

Isotopes of oxygen and hydrogen can be used to differentiate among sources of water supplying streams. Since atmospheric testing of thermonuclear devices began in 1952, ratios of hydrogen isotopes in the atmosphere have changed. This method uses the difference in "old" versus "new" water to estimate the amount of ground water flow. In order to work, the "old water" must have significant differences in isotopes than the "new water".

Tracer studies involve the addition of conservative chemical tracers to ground water to determine diffusion rates and transport of water through aquifer materials (EPA, 1991). Cornett et al., (1989) combined methods and used both tritiated (isotopes) water and chloride (tracers) to study slow ground water movement through soft lake sediments.

Advantages

Because isotopic tracers are part of natural water molecules, they are excellent tracers of water origin and movement. The use of isotopes of hydrogen and oxygen allow the study of water

movement through the hydrologic system by following the water rather than substances dissolved in the water. Concentrations are only altered by physical processes, such as mixing, diffusion and dispersion or radioactive decay. Conservative tracers can be affected by chemical reactions but may allow measurement of the velocity of ground water movement where direct measurement is not possible (EPA, 1991).

Disadvantages

A disadvantage of tracer studies is that most chemical tracers are not truly conservative. They may interact chemically or physically as they move through subsurface materials. Several disadvantages may arise in the use of isotopic tracers, also. Conditions for their use are not met in every event, and sample analysis is expensive. In some catchments, the isotopic content of "old" and "new" waters is not distinguishable, and variability in the "new water" isotopic component may decrease the precision of the separation (EPA, 1991).

Direct Seepage Measurement

Ground water seepage rates into or out of lakes and streambeds are measured at the point of discharge using seepage meters, mini-piezometers or harpoon piezometers. Seepage meters are relatively simple devices constructed of the upper or lower portion of a 55 gallon metal drum to which a partially filled pliable bag is attached (Lee, 1977). The positive or negative change in the water volume in the bag is a measure of the quantity of water flux through the lake bottom. By collecting water from the bag for analysis quality of the seepage water can also be determined. All the other monitoring devices yield indirect information of seepage into or out of a lake; the seepage meter returns direct quantities of water for the area it covers.

These devices measure seepage at a specific location. Several installations are used to characterize larger areas of a lake or streambed. As with any sampling method, the point measurements obtained represent moments in time and space. To estimate quantity and quality of ground water discharge to surface water, interpolation between data points is necessary.

Advantages

Seepage meters and mini-piezometers provide a simple, direct method to measure the quantity and quality of ground water discharge to surface water. There is no need to determine the hydraulic conductivity of the sediments. The fact that sampling and flow measurements are made in or near the sediment surface can provide an accurate indication of the contaminant inflows at the point of discharge.

Disadvantages

The inherent variability of most sediments requires a large number of spatially distributed measurements to characterize discharge and loading rates accurately. Use of this method over large areas requires a substantial commitment of human resources.

The bags used to collect seepage water can cause backpressure, which can affect seepage rates. Water quality can also be affected by artificial conditions within the seepage meter.

Combination of Methods

In the Oakwood Lakes-Poinsett RCWP project, a combination of near-shore ground water studies and direct measurement of seepage was used. The lake and the area immediately around the lake were instrumented with regular land-based monitoring wells, in-lake

monitoring wells, and seepage meters. A number of existing monitoring wells were used by the project, but others were rejected because they were screened in deep aquifers unlikely to affect the lake. To avoid confusion regarding which monitoring wells are being discussed, the small diameter in-lake monitoring wells will always have the prefix "in-lake" and standard monitoring wells located in on-shore areas around the lake will be referred to as land wells.

Considerations in combining methods to measure surface water/ground water interactions include:

- **Use land wells placed around the periphery of the lakes to determine ground water flow directions, potentiometric heads, ground water gradients, and water quality.**

- **Use small diameter in-lake wells situated within the lake to measure hydrostatic pressure gradients, and to allow for the collection of ground water samples for chemical analysis.**

- **Use seepage meters on the lake bottom to measure the inflow or outflow of water passing through the lake bottom. Water samples for chemical analysis can also be collected if the meter is located in inorganic sediment and has a high flow rate.**

- **Monitor the level of the lake to determine its relationship to ground water potentiometric head since differences between the two will govern the rate of seepage into or out of the lake system.**

- **Locate seepage meters with in-lake monitoring wells to allow the determination of volumes of seepage in conjunction with measured gradients in the in-lake monitoring wells.**

Choose Monitoring Sites

The method chosen to measure surface water/ground water interactions will affect the remaining choices of monitoring sites, parameters, sampling methods, etc. It is not appropriate to cover all of the possible combinations for each method here. Much of the remaining discussion will focus on the combination of methods used in the South Dakota RCWP project.

Once existing data have been reviewed, additional data collected, and study design and methods developed, monitoring sites can be selected. Initially, sites will be selected based on what existing information indicates about the system. Selection of monitoring sites will also depend on the method chosen to measure or estimate ground water/surface water interactions. For the direct measurement methods, monitoring sites should be located in representative sediments. They should also be located in patterns that are able to detect differences in seepage that may occur as the distance from shore increases. After some sites are instrumented and monitoring begins, additional sites may be added to better define areas of the lake or streambed with high spatial variability.

In-lake monitoring wells, seepage meters and land wells should be considered as components of a single monitoring system. Placement of one will affect the others. Previous research indicates that gradients and seepage decrease in roughly a logarithmic fashion with distance from shore (McBride and Pfannkuch, 1975) and that ground water movement is generally toward the lake basin (Winter, 1978). Discharge of ground water is also concentrated into embayments due to distortion of equipotential lines caused by a bay's penetration into the ground water system (Cherkauer and McKereghan, 1991). These factors should be considered during selection of sites before placement of the instrumentation.

In the Oakwood Lakes-Poinsett RCWP project the sand and gravel isopach map (Figure 10) and the ground water flow map (Figure 11) were used to choose locations for ground water monitoring wells. Eight in-lake monitoring well locations were identified in the monitoring plan. This was modified during installation to account for final locations of land wells. Land wells and in-lake wells were located in transects extending toward the center of the lake basin in several locations. Since the cost of installing additional in-lake monitoring wells was low (once the installation equipment was assembled), 14 locations were instrumented. A total of 21 in-lake monitoring wells were installed. At six of the 14 locations, a nest consisting of two in-lake wells was installed.

Steps to take in selecting monitoring sites:

- **Determine locations for monitoring wells based on the estimated system flow paths.**

- **Collect additional data as necessary including additional drilling in areas with incomplete information.**

- **Contact the landowners in the areas where drilling is required.** Many landowners around a lake will support studies to improve or protect their lake and will be very cooperative. Others may not want the inconvenience of having holes drilled on their property. Drilling may be restricted to areas where little damage or inconvenience will occur.

- **In-lake wells, seepage meters, and land wells can be located in transects to detect spatial variations in gradients and chemistries from on-shore locations out toward the center of the lake basin.**

- **Select transects for seepage meters and in-lake wells that are representative of the lake basin.**

- **Build flexibility into the plan so additional sites can be added after monitoring at the original transects begins.**

- **Locate in-lake monitoring wells in pairs, a deep and a shallow well, to determine vertical gradients and to detect changes in ground water chemistries as water passes through the sediments toward the lake.**

Select Parameters To Be Analyzed

Chemical analysis of water collected from in-lake wells, land wells or seepage meters is a necessary part of the monitoring design if loadings of contaminants are to be determined. Some parameters should be measured every time samples are collected, while others may be measured only occasionally to characterize the chemical nature of the water.

Every sampling point selected and every parameter measured should be justified based on how it meets the identified monitoring goal. This may seem obvious, but many projects monitor parameters that are not needed. Sometimes this is done because of what was measured on the last project or sometimes an established list of standard parameters is used on all projects within an agency. Customizing the parameter list will save resources. The final design should conform to budgetary constraints while yielding the maximum amount of information.

In The Oakwood Lakes-Poinsett RCWP Project land wells, in-lake wells and seepage meters were analyzed for the following chemical parameters:

1. total dissolved phosphorus
2. ortho phosphorus (soluble reactive)
3. nitrate
4. nitrite
5. ammonia
6. total Kjeldahl nitrogen
7. total dissolved solids
8. chloride
9. sulfate

KEY LESSONS LEARNED: Measurement of chloride, sulfate and total dissolved solids helped characterize waters collected from different measuring devices and different aquifer areas. These somewhat conservative parameters were useful to help determine the source of water collected in seepage meters and in-lake wells.

Choose Sampling Methods and Equipment

Care taken in choosing sampling methods and equipment will enhance the collection of high quality defensible data sets. Refer to the **GROUND WATER MONITORING** section for selection criteria methods and equipment for land wells. The same criteria can be applied to in-lake wells and seepage meters. In-lake wells are very similar to land wells except that equipment must fit into a small diameter well, which limits the size of the sampling device. Seepage meters can be sampled by simply removing the bag used to measure water volume.

Determine Sampling Frequency

The frequency of data collection will depend on how dynamic the system is that is under study. Frequent changes in flow or in concentration of contaminants will require more frequent sampling. If little change occurs over time, sampling schedules can be reduced or redirected to periods of time when the system is changing rapidly. Review of the seepage and water quality data early in the project may allow adjustments in the frequency of sample

collection, resulting in a more efficient project. This is especially true of long term projects with data collected over several years.

Frequency of sampling will also be affected by the project budget. Planned periodic sampling of wells and seepage meters is preferred. Evaluation of data and calculation of loadings is simplified if regular intervals are used.

Develop Quality Assurance/Quality Control Procedures

The importance of a program to insure the collection of quality data is discussed in the **Nonpoint Source Project Elements**. Quality assurance will include both field and lab procedures. Most laboratories will have a published quality assurance/quality control manual that can be reviewed, updated if necessary, and attached as an addendum to the monitoring plan. Quality assurance for installation of monitoring equipment and collection of data in the field depends on the methods chosen and will be different for each project. Standard operations procedures for drilling land well, and in-land well installation, seepage meter installation, collection of water samples and collection of field measurements should be developed and included in the monitoring plan. Standard operations procedures and a good training program will help insure the consistency of the data collected. This is particularly important for long term projects where turnover in personnel is more likely to occur.

In addition to operating procedures and training quality assurance/quality control involves procedures that provide a measure of how good the data is. In the South Dakota RCWP project, blind duplicate samples (for precision) or spiked samples (for accuracy) composed 10% of the water quality samples submitted to the laboratory. These samples were in addition to the analysis of control samples, blanks, spikes and duplicates described in the laboratory quality assurance program. The purpose of the field prepared duplicate and spiked

samples was to document the quality of the data from sample collection through laboratory analysis.

To document the quality of field measurements, duplicate (actually consecutive measurements on the same day) seepage meter readings were collected at each seepage meter. This provided a measure of how reproducible individual seepage meter measurements were. At one location two seepage meters were installed in close proximity and measured repeatedly to determine the amount of variation between individual seepage meter installations. The concept of installing multiple meters at each location was considered but dropped due to the costs involved.

Establish Data Handling and Storage Procedures

A monitoring network to measure surface water and ground water interactions can produce a large amount of data. The monitoring plan should account for the hardware, software, and personnel needed to enter and store the data.

Some laboratories provide results of analysis on electronic media but more commonly a printout of the results representing each sample submitted will be received. Data from paper lab reports and filed notebooks must be entered into a database. Database programs like D Base, Alpha 4, and others are designed to make data entry and retrieval easy. With little effort, the data entry format can be customized to match the lab report form or the field notebook format.

Data from the database type programs can also be down loaded to a spreadsheet format such as Lotus 1-2-3, Quattro Pro, Excel, and others. Data can also be entered directly onto spreadsheets that have been developed specifically to handle each type of data. Much of the data from field notebooks can be handled in this way. Whether the data is "dumped" into a

spreadsheet program or entered directly, the spreadsheet can be used to manipulate data and prepare graphs used in data evaluation.

- **Verification of the accuracy of the data is important.** Before data evaluation begins the data should be printed out and double checked for accuracy back to the original lab reports or field notebooks.

- **Back up data on a regular basis.** Create backup files and rotate them so one copy is out of the loop to prevent backing up damaged files.

- **Keep backups in more than one location.** This prevents loss of entire data sets in case of fire or other calamity.

- **Make copies of field data sheets of notebooks regularly to prevent loss of previously collected data.**

MONITORING SYSTEM INSTALLATION

Once the monitoring project is planned, the next step is to put the instrumentation in place and start collecting data. Important considerations are **construction of equipment, installation techniques, and data collection.** Construction details include the type of materials that will be used for each well or seepage meter, the diameter and length of various parts, and the seals and supports that will be needed to hold each one in place and isolate the sampling point. Installation techniques involve the methods that are used to obtain satisfactory placement of each device in the chosen location.

Construction

In-lake wells

In-lake wells are smaller versions of standard monitoring wells that are used to determine the gradient of ground water and collect samples at various points below the lake bottom relative to the lake surface.

In the Oakwood Lakes-Poinsett RCWP project in-lake wells were constructed using one-inch diameter PVC pipe with fiberglass cloth epoxied over an area perforated with 1/8 inch holes at the end of the pipe. A pipe cap was glued on the end of the pipe to complete the construction (Figure 12).

Figure 12. An in-lake well with a fiberglass screen.

Considerations and steps to take in construction of in-lake wells are:

- **Construct in-lake monitoring wells with a small diameter pipe to reduce the amount of water that must be removed from the system during sampling.** This is especially important in till and other tight sediments that contain little water and are more likely to be affected by removal of water than sand and gravel.

- **Use inert materials for the well casing such as PVC.** Metal pipe is not recommended unless it is corrosion resistant.

- **Use short screens to ensure discreet measuring points.** Long screen will result in a mixed sample from several depths within sediment.

- **Fiberglass cloth, epoxied over slots or drill holes, provides an inexpensive, fine slotted screen that is easy to install.**

Seepage Meters

Considerations and steps to take in construction of seepage meters are:

- **Seepage meters are constructed by cutting off the top portion of a 55-gallon drum.** Drums with a large threaded bung hole work best. Standard plumbing connectors are used to connect a nylon nipple to the drum. Thick walled flexible tubing and clamps are used to attach a rigid tube to the nylon nipple. The rigid tube can be adjusted for the depth of water. The bag may be attached directly to the nipple in shallow water or at the end of a rigid tube in deeper water (Figure 13).

- **In areas with soft, deep mud, whole barrels can be converted into seepage meters.** If the meter fills with sediment during installation a longer meter must be used.

Figure 13. A seepage meter ready for installation.

Land Wells

See the **GROUND WATER MONITORING** section for a detailed description of considerations for the construction of land based monitoring wells.

Installation

Installation of monitoring devices will require the mobilization of equipment such as drill rigs, coring devices, and specialized equipment for work in lakes and rivers. Extra personnel will also be required. Installation of seepage meters and in-lake wells in shallow water can be accomplished by simply wading out to the desired location. In water which is over waist deep, however, some type of platform will be needed.

Welch and Lee (1989) describe a work platform consisting of two boats with a plywood platform between them. It was held in place by a large anchor offshore and lines to points onshore. The platform was used to successfully install flexible piezometers and for piston coring.

In the South Dakota RCWP project a floating barge was constructed to install intake wells and seepage meters as well as collect sediment cores (Figure 14). The barge was moved from place to place by towing or attaching a small outboard motor to the beam (Figure 15).

In-lake wells

Considerations and steps to take in installation of in-lake wells are:

- **Install in-lake wells and seepage meters from a platform that is held firmly in place over the work area.**

- **Maintaining the platform in a stationary position over the work area will probably be a problem during installation of in-lake equipment.** Wind or any lateral force applied to seepage meters or in-lake wells during installation will cause a free floating platform to move away from the point of installation. Movement of the

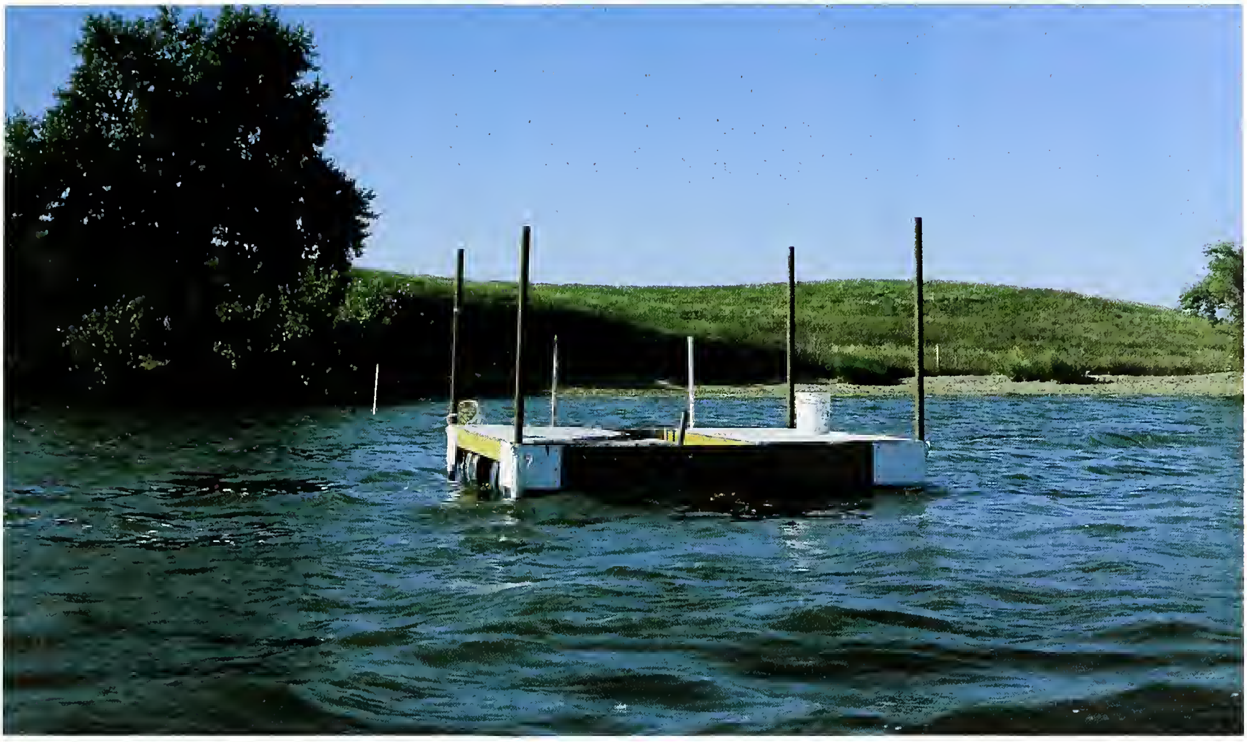

Figure 14. A floating barge used to install seepage meters and in-lake wells.

Figure 15. Moving the floating barge.

platform will cause the well or seepage meter to tip over before installation is complete.

- **Collect sediment cores with a piston type sampler at each site where in-lake wells and seepage meters are installed.** Sediment cores help to determine sediment composition and estimate hydraulic and chemical properties of the sediment (Figure 16).

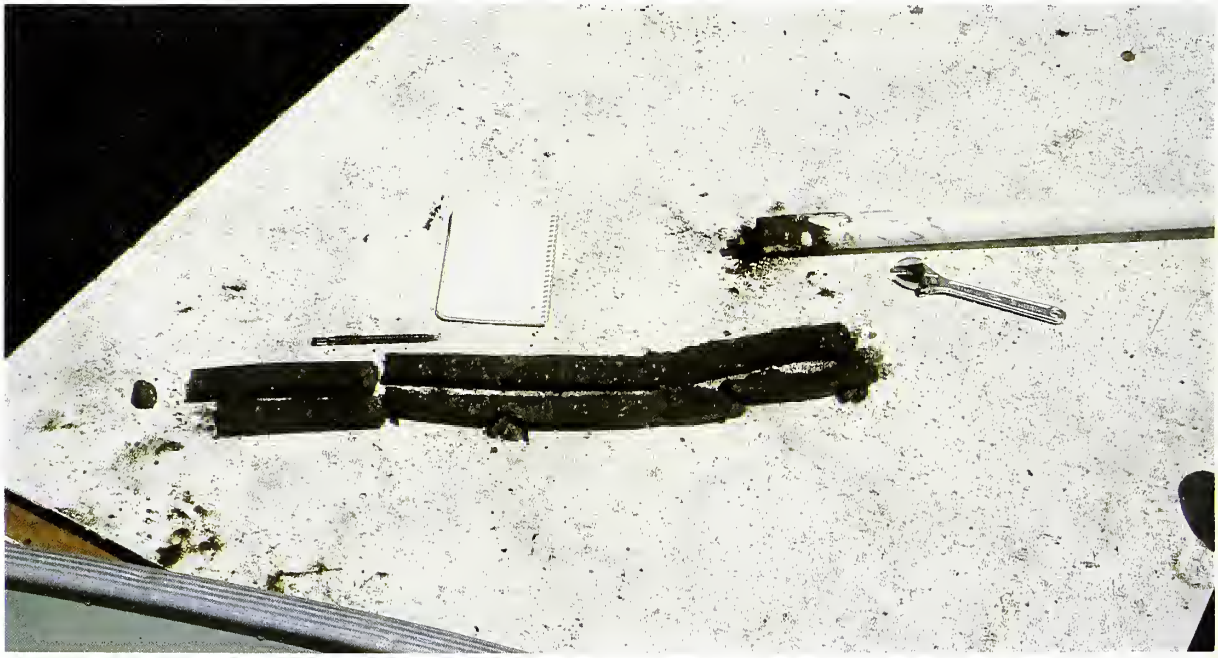

Figure 16. Lake sediments collected with a piston corer.

- **Use a steel tub with a drive point on the end to drive the well into the lake bottom to the desired depth.** Insert the in-lake well into the tube and hold it in place while the tube is withdrawn, leaving the in-lake well and drive point in place.

- **Use bentonite and a collar around the base of the well at the lake bottom to seal the well, give the well strength, and help keep the bentonite in place.** Dry bentonite is mixed with water to a very thick consistency, rolled into logs, and placed at the annulus of the well by diving before the support stand is installed.

- **Use a support stand around the base of the well to maintain an upright position.** This will keep the well from pulling out of soft sediment. It can be weighted to the bottom with large cobble size rocks. The bottom of the support stand covers the bentonite seal around the well and protects it from wave action.

Seepage Meters

In the South Dakota RCWP project, seepage meters were installed in shallow water by wading to the site and in deeper water using the barge. Several of the locations were coordinated with land wells and in-lake wells to provide transects beginning onshore and extending toward the center of the lake.

Considerations and steps to take in installation of seepage meters are:

- **Seepage meters are placed on the lake bottom and driven or pressed into the sediments.** Installation varies with the type of sediment present and the depth of the water.

- **Adjust the rigid tube from the meter to near the water surface to allow access to the seepage meter bag without diving.**

- **In hard sediments install seepage meters using a tamping device designed to protect the meter from damage as it is driven into the sediment.** A post driver and

a modified steel post can be used to tamp the meter into the sediments. On rocky substrate, some rocks may have to be loosened and removed to complete an installation.

- **In soft sediments, meters can be pressed into the lake bottom until firm sediment is contacted.** Keep the bung hole open until the meter is in place, then dive to the meter and attach the tube assembly. In water over four feet deep, standing on the meter to press it into the sediment, does not work. A small platform with legs extending down to the meter can be used to reduce the buoyancy of the installer. Stability is improved if the platform legs are clamped to the top of the meter. The weight of one or two installers is usually sufficient to press meters in soft sediment.

- **Use gentle tamping while standing on the top of the meter rather than hard driving strokes that may deform the edge of the metal drum.**

- **If the sediment contains rocks, the seepage meter can be sealed around the edge with a bentonite ring.** The bentonite fills gaps left by small stones that were removed and prevents a hydraulic connection with the lake water. The bentonite is mixed to the proper consistency and molded to the outside of the meter before it is placed in the water.

- **If the meter will be subject to wave action, truck tire innertubes can be installed to protect the bentonite seal.** Split the tube in half to form two circular flaps. Stretch the flap over the seepage meter to form a skirt above the bentonite. After installing the meter, place rocks on the innertube to hold it in place

A complete installation for measuring ground water interchange with the lake is shown in Figure 17.

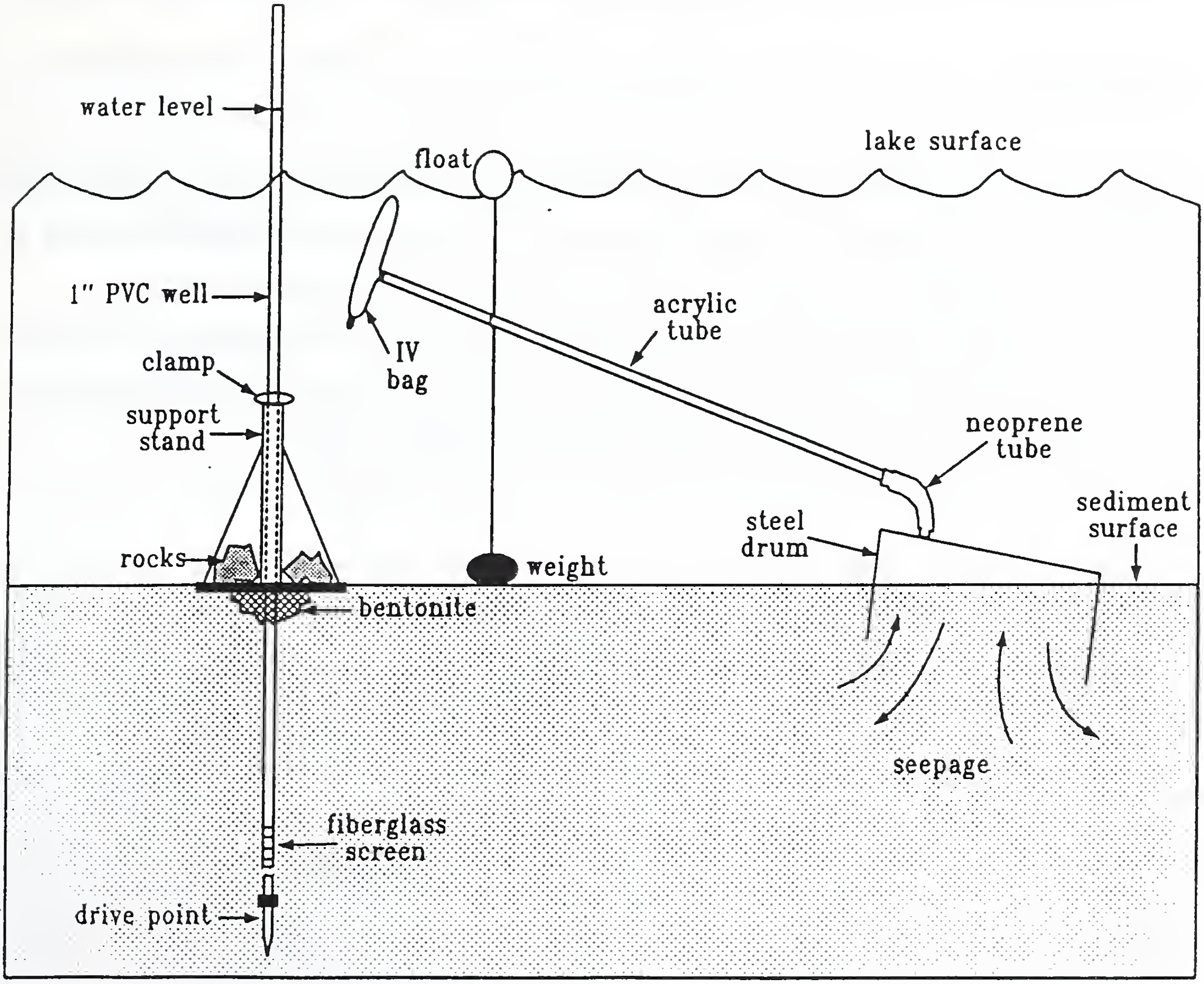

Figure 17. A typical seepage meter and in-lake well installation.

KEY LESSON LEARNED: A stable work platform was a necessity to install in-lake wells and seepage meters and to collect sediment cores. A floating barge was constructed that could be raised completely out of the water on four support legs. The barge was raised by pulling down on a lever placed on the support legs and then tightening a set screw. To move the barge the legs were pulled out of the mud by shifting the crew to submerge one corner, tightening the set screw, and then shifting the crew to another corner. The buoyancy of the barge would dislodge the stuck leg.

Land Wells

Land wells can be installed at various depths to measure horizontal and vertical gradients and identify chemical stratification. They can also be used to test aquifer characteristics such as hydraulic conductivity. Accessibility in terms of landowner cooperation and ability to transport sampling and other monitoring equipment to the site is a consideration in location. The steps to take in construction, installation, and placement of land wells are the same as those described in the **GROUND WATER MONITORING** section.

In the Oakwood Lakes-Poinsett project wells were installed at a depth of approximately 5 to 10 feet below the water table when the water bearing strata was sand and gravel. The wells were constructed of 2-inch diameter PVC pipe coupled to #18 slot well screen, usually 3 foot in length. Wells were placed near the water table and near the bottom of an unconfined aquifer and in the upper part of a confined aquifer which was separated from the overlying unconfined unit by an aquatard. During the drilling to install the land wells, split spoon samples were collected so that the geology could be further defined. A more detailed isopach map of sand and gravel contours was constructed. The final land well array evaluated inflow to the lake from all directions except the northeast side which was predominantly glacial till material not likely to be a major contributor. Outflow to the southeast was also evaluated.

Data Collection

In-lake wells

After in-lake wells are installed they should be purged several times with a peristaltic pump or other similar device to remove water affected by the installation procedure. This is similar to the well development procedure discussed in the **GROUND WATER MONITORING** section. When development is complete, in-lake wells should be allowed to stabilize. Water

level measurements are taken before the wells are purged and sampled. Since these wells can be purged completely prior to sampling, they can be used to obtain samples of ground water below the lake bottom that has not been affected by artificial enclosure, which often results in an anoxic environment.

In the Oakwood Lakes-Poinsett RCWP project, samples were collected from the in-lake monitoring wells with a peristaltic pump which could quickly evacuate the small diameter wells. In-lake wells finished in sand and gravel recharged quickly and could be sampled immediately, but wells finished in glacial till were sampled the following day.

Figure 18. Measuring water levels with a beeper pole.

Water levels for in-lake wells were measured using a "beeper pole" which was inserted into the in-lake well and registered a beep when electrodes contacted the water surface inside the well (Figure 18). The distance to water was determined by reading a fiberglass tape imbedded in the rigid and transparent beeper pole. The water level outside the well measured to the top of the well was also determined with the beeper. A short piece of pipe similar to the well was used to still the lake surface for the measurement outside the well. Inside and outside water levels were measured to the same point on the

top of the in-lake well. The difference in the two measurements represented the gradient at that point.

Seepage meters

Seepage meter readings are collected by attaching a bag containing a known amount of water to the meter. The bag is recovered after a period of time and the volume is remeasured and the time interval is recorded. The volume of water gained or lost is divided by the amount of time the bag was attached and the area of sediment covered by the meter, to yield the seepage rate. Water quality samples can be collected from the bag if the meter does not become anoxic. Dilution of the sample with the initial water in the bag must be accounted for.

Figure 19. Measuring water levels.

Land wells

Water levels in land wells were measured by using a popper (Figure 7) on the end of fiber glass tape lowered into the well (Figure 19). Land wells were sampled with submersible bladder pumps or bailers, depending on the site accessibility, well recharge capability, and weather conditions.

Considerations during sample collection include:

- **Preserve the samples and transport them to the lab.** Recommended preservatives and holding times should be observed (US EPA, 1982). Procedures will vary for each parameter so several bottles may be needed.

- **Conduct field filtration if necessary.** Some parameters may require field filtration. A battery powered peristaltic pump can be used for either suction or pressure filtration. A portable lab bench in the monitoring vehicle is useful.

- **Ground water monitoring wells can be sampled with submersible bladder pumps, bailers or peristaltic pumps, depending on the conditions.**

- **Water levels of in-lake wells are best measured on calm days to allow accurate measurement of the lake level relative to the water level in the well.**

- **Attach intravenous (IV) bags partially filled with water to seepage meters to determine rates of seepage into or out of the lake based on the amount of water lost or gained in the bag. The IV bags are very pliable, have an injection port that snaps into the proper size tube and are very inexpensive if used ones are available.**

- **Check seepage bags within one to 24 hours of attachment to prevent over filling of the bag. Back pressure due to full seepage bags will inhibit movement of water into the bag.**

KEY LESSON LEARNED: Seepage meter samples were not good indicators of water quality when located in organic sediments. Anoxic conditions developed in the overlying water when some sediments were enclosed. Belanger and Mikutel (1985) reported changes in water chemistries under anoxic conditions.

DATA ANALYSIS DESIGN

In any monitoring project there is rarely, if ever, enough instrumentation installed to completely cover the area being investigated. Therefore, interpolation between measuring points for both flow and water chemistry is necessary. In its simplest form the following steps need to be followed to determine the seepage through a lake bed:

- **Establish compatible formats between different sets of data (seepage meter, in-lake monitoring wells, land monitoring wells).**

- **Calculate seepage rates at every available measuring point.**

- **Delineate areas with similar seepage rates for each time segment and measure the total area of each using a planimeter on maps drawn to scale. Since seepage rates are not the same at all times the size of areas represented by a particular seepage rate may vary.**

- **Multiply seepage rate by the area representing that rate and express it as a cumulative quantity of water. Summing the quantity of water produced or lost by all segments of the lake bed yields the net gain or loss of ground water to the surface water body.**

- **Delineate areas with similar chemical characteristics. This step may need to be repeated for each chemical parameter of interest.**

- **Since chemistries are not the same at all times, determine time blocks of "steady state" chemical concentrations. As in steps two and three, an iteration between steps five and six will probably be necessary until a combination of "steady state" concentrations and areas of similar concentration are achieved.**

- **Overlay chemical concentrations and appropriate time periods of quantity of water calculated. Multiply chemical concentration times quantity of water to determine loading to the lake.**

The first step (calculate seepage rates at every measuring point), varies from the easiest to the most difficult to accomplish. Where there is a properly working seepage meter, the calculation is straightforward. Gaps in data between readings may be determined by straight line interpolation, by establishing a relationship with adjacent seepage meters, or by establishing a predictive relationship with another measuring instrument.

Establishing a predictive relationship with other instruments is not only desirable as a way of determining seepage when the seepage meter is no longer present but also because measurements at seepage meters are somewhat labor intensive. A desirable system of measuring seepage would be collecting water levels from land wells in conjunction with lake elevations. With knowledge of the hydraulic conductivity and effective porosity of the aquifer and lake bottom, combined with the gradient calculated from ground water and lake level, a velocity for the ground water can be calculated. The equation for the average linear ground water velocity is:

$$A.L.V. = K * I / n$$

A.L.V. = average linear velocity
K = hydraulic conductivity
I = gradient
n = effective porosity

The last variable needed is the area of receiving or discharging lake bottom. This has to be determined initially by actual measurements. Flow velocity multiplied by the area yields a quantity of water.

Difficulty arises in determining the effective porosity, (usually estimated from references based on particle distribution of the material), especially on the lake bottom. Hydraulic conductivity of the aquifer can be determined by pump tests or single well slug or bail down procedures. In-lake monitoring wells may allow similar tests but the most important hydraulic conductivity needed for accurate quantity calculations is the limiting hydraulic conductivity. This is most likely located within the strata that comprises the lake bottom sediments. The in-lake monitoring well being tested may or may not be located in this limiting layer.

To overcome these difficulties, integration of various data sources is necessary. As mentioned earlier, delineation of the area of lake that is receiving or discharging water is required. The most direct method would be the installation of seepage meters. Establishing the numerical relationship between seepage meters and the in-lake monitoring well gradient serves a multi-fold purpose. Once the relationship is derived and the effective porosity and hydraulic conductivity are known, they are combined into one term.

$$Q = A * (K * I / n)$$

Q = volume of water seepage
A = area of lake bottom

By establishing the seepage meter gradient relationship, area becomes some unit area (Q/a), hydraulic conductivity and effective porosity become a constant (Kn) and the equation becomes:

$$Q/a = I * (Kn) + \text{constant (from the numerical relationship equation)}$$

In the Oakwood Lakes-Poinsett RCWP Project, two aquifers, one confined, and the other shallow and unconfined, were located in the vicinity of the lake. It was difficult to determine which aquifer was contributing water to the lake. Land well water chemistries from different depths and aquifers were compared to in-lake well values. Values for phosphorus did not vary significantly so an average value was used. This simplified the calculation of loadings to the lake.

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VADOSE ZONE MONITORING

INTRODUCTION

In the development stages of a nonpoint source subsurface water quality monitoring project, the obvious initial question: where, when, and what monitoring should be done? In the subsurface environment, the "where" in this question relates to not only a horizontal dimension but also a vertical dimension. The vertical dimension refers to the unsaturated and saturated zone. The unsaturated zone includes both the root zone and the unsaturated zone beneath the root zone.

Additional questions in the planning process are: 1) should both the unsaturated and saturated zones be monitored? and, 2) if so, what information will be derived from data gathered in each zone? The answers to these questions have to be related to the objectives of the project to formulate the answer.

A key question to ask in the project development stage relating to the vadose zone is: Is the objective to evaluate water quality concentration changes, or is it to evaluate mass loading changes as the result of a management practice change? Monitoring concentrations does not always give a complete picture or understanding of fate and transport of solutes moving to an unconfined aquifer. Concentrations give an instantaneous description in time of the solute taken from a given area.

In the South Dakota RCWP project, monitoring concentrations of nitrates in the saturated zone consistently showed higher levels of nitrates in water samples collected from wells placed in glacial till soil compared to samples from wells placed in outwash. This probably was a dilution factor phenomena based upon the effective porosity of the materials. However, it was inconclusive whether there was more mass of nitrate-nitrogen recharging the ground water on the glacial till or the outwash sites. This was never a goal of the ground water monitoring

plan, but it demonstrates that inconclusive results may occur if the solute carrier and the solute concentration are not evaluated in transport studies.

In the planning stages, it is important to know the requirements for accurately monitoring each zone. Simply stated, monitoring agrichemical transport to the ground water would be simplified if the water reaching the saturated zone could be sampled just before it arrived at the water table. This water could be analyzed for concentrations of specific parameters, and the volume of water could be measured to determine the total loading of water and solutes to the ground water. If sufficient samples are collected in space and time from within the vadose zone, inferences can be made regarding contaminant fate and transport under the applied land management practices.

The procedures used to meet the monitoring objectives may be approached either from the saturated zone, the unsaturated zone, or both. Each method has advantages and disadvantages. If determining the agrichemical loading to the ground water resulting from differences in management practices is a primary objective of the project, monitoring recharge water is important. The free draining water reaching the water table as recharge should be collected to calculate the loading to the ground water. If the approach to collect this water is done from the saturated zone, there is the confounding problem of collecting a high percentage of existing water in the saturated zone with the downward percolating water, which may drastically affect the loading calculations. Conversely, if the approach is to sample the unsaturated region above the water table using unsaturated instruments, there is a danger of extracting "too high a percentage of matric water" in the sample, which may not otherwise drain freely.

This section presents information and establishes reasoning for vadose zone monitoring from the South Dakota RCWP project. If a proposed project is focusing on fate and transport of potential agricultural contaminants to the ground water, an evaluation of this section and other related references are recommended reading. If the goals are to focus only on ground water

quality changes which may be occurring (refer to **GROUND WATER MONITORING** section), the unsaturated zone may be eliminated from project consideration. If the latter approach is taken, however, provisions must be taken to describe the water quality over a range of depths below water table to ensure complete characterization of the saturated zone over time.

PRE-MONITORING PLANNING AND DESIGN

What is the Vadose Zone?

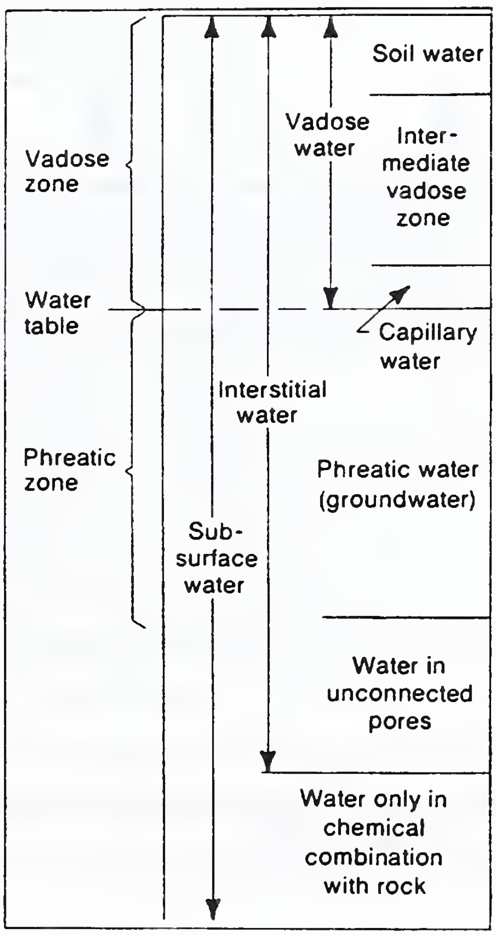

Figure 20. Classification of subsurface water. (Driscoll, 1986.)

The word vadose is an adjective defined by Webster's College Dictionary (1991) as "found or located above the water table." This definition could implicate a variety of subsurface depths below the ground surface depending upon the type of subsurface material that may be investigated. Essentially, there is ground water beneath all points on the earth. Water occurs in two types of environment, the phreatic zone and the vadose zone (Figure 20).

The only difference between points would be the make-up of the material (geology) and the depth to the saturated layer (water table).

As the water table fluctuates below the ground surface according to weather cycles, which mainly controls the recharge and evapotranspiration (evaporation and transpiration combined), the vadose zone continually changes in depth. For certain time periods, the zone may be non-existent (water table at the surface), or it may extend to many feet below the ground surface. It may include many different layers of material with varying hydraulic, physical, and chemical characteristics (Figure 21). When designing and implementing a nonpoint source monitoring system that includes the vadose zone, this phenomenon needs to be understood before of the complexity of the monitoring is fully realized.

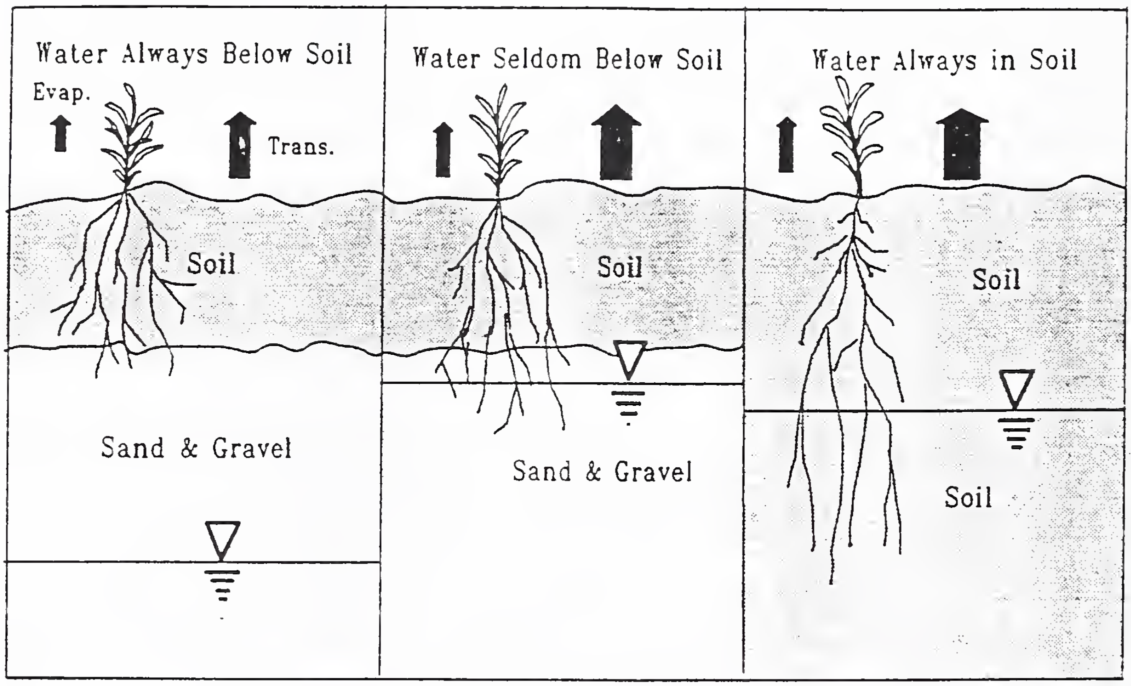

Figure 21. Examples of typical Northern Plains Region Vadose zones with varying subsurface materials and depths to the water table.

Understanding the Nature of the Vadose Zone

The vadose zone always includes the root zone. The most important characteristic of the vadose zone to understand is that it is transient (varies in depth with time). The major difference between the zone beneath the water table (saturated zone) and the vadose zone is that the vadose zone is unsaturated (many of the voids are filled with air most of the time). The area beneath the water table is saturated where the pores are filled with water. The most confounding problem in vadose zone monitoring is the transient nature of the water table. Most often, vadose zone monitoring techniques have not been simplified to handle this transient phenomena. Dedicated vadose zone instruments monitor a point both in space and time. If the saturated zone is extremely transient, several monitoring depths and locations may be needed to statistically evaluate loading of solutes carried in water moving through the vadose zone to a transient water table.

KEY LESSON LEARNED: The vadose zone is transient, which is the most important characteristic of the vadose zone to consider.

The climate, type of vegetation, and subsurface geology will control the rate of change of the water table position, and, therefore, the extent of the vadose zone. The effects of subsurface geology differences on the vadose zone can be illustrated in the following example. The recharge of one inch of water will cause an approximate 20-inch rise in the water table for glacial till material (drainable porosity = 5%) compared to a 5-inch water table rise for outwash material (drainable porosity = 20%). The differences in subsurface material between sites may also affect the chemical and biological activities that occur due to the presence or absence of oxygen within each layer of material. The chemical and biological activities may affect the physical and hydraulic characteristics of the subsurface material as well.

Investigations of the vadose zone of glaciated and non-glaciated soils and geology in the upper midwest can include up to 30-60 feet of material. Typically, the vadose zone monitored for a nonpoint source project in this region will include the top 10-15 feet of soil and subsoil. The thickness of the vadose zone, in conjunction with project objectives, will determine the number of vertical monitoring points. A 15-foot thick vadose zone may require more monitoring sites and depths than a 5-foot vadose zone.

In the South Dakota RCWP project, the thickness of the vadose zone ranged from 0-20 feet, and it fluctuated rapidly. The vadose zone decreased by eight feet (the water table moved up eight feet) within one week as a result of above normal rains in 1983.

KEY LESSON LEARNED: Typically, the vadose zone in the Northern Great Plains region monitored for a nonpoint source project will include the top 10-15 feet of soil and subsoil.

In subsurface water quality monitoring, background information on the geology and/or the water table position for on-site monitoring may not be available. In such cases, preliminary on-site investigations must be done to evaluate the nature of the subsurface environment. This area may be very small (plot size) or it may be quite large (field scale), depending upon vadose zone characteristic uniformity. Three to five sites in an area where all or most of the characteristics of the vadose and saturated zones are similar should be evaluated at the same time in these investigations to overcome the spatial variability (heterogeniety) inherent in the vadose zone.

It is important to have subsurface investigations done by both trained soil scientists and hydrogeologists to determine the nature of the subsurface environment. Soil scientists

understand the characteristics of soils; hydrogeologists understand the characteristics of saturated zones.

Temporary saturated conditions can occur under some geologies at different times, such as shown in Figure 22. Investigations with deep soil probes and augers can provide insight regarding the subsurface hydrology so data can be properly evaluated. In dense, glacial till soils and subsoils, on-site evaluations of the water table position can be deceiving because hydraulic conductivities can be extremely low. Temporarily-installed water potential sensors may be necessary to evaluate the water potential at different depths for low permeability materials.

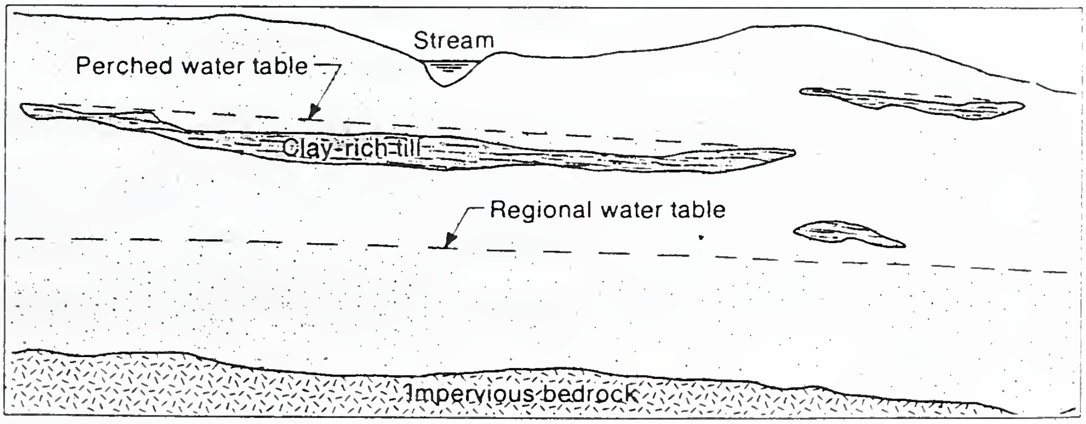

Figure 22. An example of a temporarily saturated condition above a regional water table supported by clay-rich tills low in hydraulic conductivity (Modified from Driscoll, 1986.)

Why monitor the vadose zone?

Investigative monitoring in the unsaturated zone at selected sites may provide answers to questions that arise in the planning stages of a nonpoint source pollution project. In many projects, the main reason to monitor the vadose zone is to more accurately determine the **change** in the flow of water and solutes recharging the ground water as a result of a surface management practice. If this recharge water is intercepted before it reaches the ground water, there is **less potential** for mixing "new draining water" with "existing water in the saturated zone." A more accurate loading of water and solutes reaching the ground water can then be made.

For surface waters, monitoring points are obviously selected by identifying points where flow accumulates at a specific point. These points generally represent all runoff from a specified area. The landscape has characteristics which allow for easy evaluation of monitoring site selection. For subsurface monitoring, things are not quite so simple. If it was known where the majority of the water and contaminants were recharging the ground water, there would be little difficulty locating monitoring points. Usually this is not the case. **Determining the depth of monitoring and the number of sites needed to obtain statistically significant differences in measured variables for determining fate and transport of water and solutes, are probably two of the most difficult considerations in developing a vadose zone monitoring plan.**

KEY LESSON LEARNED: Monitor the vadose zone if fate or transport of contaminants and mass loading of solutes to the ground water is a project objective.

The vadose zone is quite complex because of the various biological, chemical, and hydraulic changes which occur over time. As an example, for fate studies, a pesticide which may be detected in the soil water at a given depth, may be degraded to less harmful metabolites within a few days, or it may have been diluted to smaller concentrations with capillary or macropore drainage water. Water samples which have concentrations of substances lower than the detectable limits are not desirable for fate data evaluation.

KEY LESSON LEARNED: To obtain a good data set of vadose zone water quality for the project parameters proposed, this general rule should apply: **if the tested parameter is close to the minimum detection limits, monitoring closer to the source and sampling more frequently is recommended.**

Characteristics of the Vadose Zone

Physical

The vadose zone tends to be heterogeneous, although there are places where soil and subsoil can be homogeneous. If the latter case applies, monitoring of soil water becomes less complex. Following is a list of the physical characteristics which affect vadose zone monitoring design:

1) topographical position
2) soil aspect (relationship of soil slope to the sun angle)
3) slope
4) soil texture
5) soil structure
6) soil surface conditions (bare, annual crops, or perennial crops)
7) number of soil horizons

8) soil horizon pore size distribution
9) bulk density
10) particle density
11) porosity
12) soil clay mineralogy
13) depth of the saturated zone
14) homogeniety of the vadose zone

As climate variations (temperature, rainfall, radiation, etc.) occur, and surface management practices (tillage, crop, fertilizers, soil amendments, etc.) are implemented, gradients are induced in many of the forces acting within the vadose zone. Because the ecosystem is continuously trying to reach equilibrium in response to the external forces, there is a continual dynamic effect of changing physical, chemical, and microbiological characteristics. Many of these responses to the external forces occur in short periods of time, whereas others may take years to equilibrate. Physical changes in the vadose zone can affect chemical and microbiological changes, and subsequent changes in the microbiological and chemical effects can, in turn, affect either the same, or different, physical characteristics.

Prominent physical considerations of the soil affecting the monitoring design is the soil texture, whether the texture is uniform with depth, and whether there are abrupt boundaries where texture changes are severe. Some vadose zone sampling devices work better in some textures than others. Abrupt textural changes in the soil horizon also affect the way water moves from one layer to another, either upward or downward flow. As an example, the downward movement of water in a finer textured (more clay) soil abruptly changing to a coarse textured soil can move very quickly and with preferential fingering once it crosses the boundary. Certain vadose zone instruments need to be used in such cases if this water is to be evaluated for quality and/or quantity. Refer to the **Vadose Zone Monitoring Equipment and Procedures** on page 182 for more information.

Hydraulic

The hydraulic characteristics of the vadose zone are usually measured properties which are affected by other characteristics of the vadose zone. Texture, bulk density, and pore size distribution alter the way water moves in and out of the soils and affects the hydraulic properties. Some of these measured hydraulic characteristics are:

1) water characteristic curve which describes the soil water content at different soil water pressure potentials for a given soil (often referred to as matric potential or energy level of the water)
2) wilting point
3) field capacity
4) drainable porosity (drained depth of water per unit depth of soil)
5) capillary rise
6) bubbling pressure (soil water tension at which air enters the soil)
7) macroporosity
8) saturated and unsaturated hydraulic conductivity
9) saturated water content

For more information regarding these parameters, refer to the many soil physics books available (suggested reference: Jury, et al., 1991).

Chemical

There are many chemical characteristics of the vadose zone which should be considered when designing a vadose zone system. These include the following:

1) salinity (higher soluble salts in soils tend to have higher soil water contents)
2) pH

3) exchangeable sodium percentage (ESP) (higher ESP's tend to reduce hydraulic conductivity)

4) cation exchange capacity (CEC) (higher CEC soils usually have higher water holding capacity)

5) the organic matter content (%)

6) the carbon to nitrogen ratio (C:N)

Biological and Microbiological

The aerobic and anaerobic microbe population at different depths impacts the decomposition rate of residue, organic matter, and other organic substances. This can affect the chemical and physical characteristics of the soil. Earthworms and other biota contribute to the pore size distribution, which in turn affects the soil water flow. The preferential bypass flow may increase substantially if this population is high and no-tillage is practiced for extended periods of time (Bischoff, in progress).

The dissolved organic carbon (DOC) concentration in soil water at various depths within the vadose zone may increase the carbon to nitrogen ratio. Microbes need a carbon source to degrade nitrogen compounds, and many times carbon is the limiting nutrient in subsurface zones where shallow ground water exists in highly permeable formations. The DOC is usually very water soluble and can represent a large portion of the carbon carried by percolating water.

Subsurface Geology

Impacts of lateral pressure and flow in highly permeable formations from off-site ground water recharge, or from rising water from adjacent stream flows (Figure 23), can affect the water table position, and thus, affect the vadose zone. In highly permeable formations where lateral subsurface flow from off-site recharge areas may occur, instrumentation re-evaluation, or

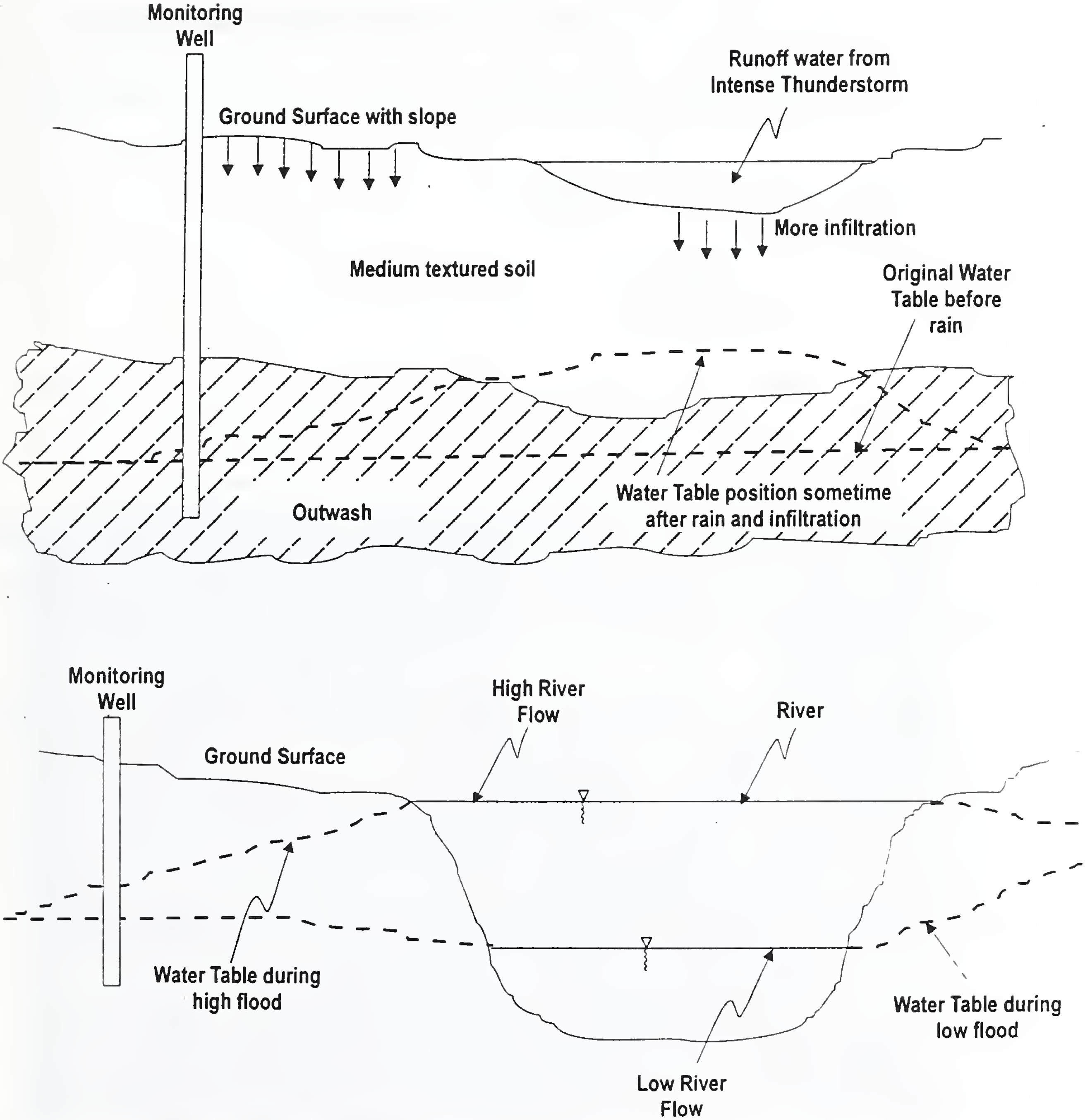

Figure 23. Two examples of lateral effects of off-site water impacting monitoring points.

relocation of a monitoring site may be necessary depending upon your objectives. If the water table is monitored to determine on-site recharge from rainfall, lateral pressure caused by mounding conditions from nearby higher recharge areas can cause problems in calculations for loading of water and solutes through the vadose zone

Factors Impacting Vadose Zone Conditions

Soil Infiltration and Variable Rainfall

The variations in intensity during rainfall events has a significant impact on the amount of overland flow that takes place. Sites with slope are affected more than sites that are level or near level. Surface water storage characteristics can vary significantly depending upon vegetation, antecedent soil water content, and surface roughness. Infiltration of rainfall into the soil is highly variable, depending upon rainfall intensity, depth, soil texture, soil slope, surface roughness, tillage practices, and crop cover conditions.

Water movement into the soil is more uniform during long gentle rainfall events which usually occur in the spring and fall in the Upper Midwest. There is adequate time for water to move into the soil before ponding and runoff conditions occur. For intense rainfall events, surface runoff begins soon after rainfall begins, even before the soil becomes saturated. Water begins to run off to lower positions on the landscape. Under these conditions, infiltration and subsequent recharge of shallow aquifers may occur in specific lower topography positions.

Differences in infiltration rates at different locations on the landscape affects monitoring site selection. It is important to locate study sites on sites representative of the watershed and/or aquifer under scrutiny. If loading calculations for the watershed are extrapolated from study site data, it is important to locate the sites in areas representing the entire area in question.

Low lying areas tend to over-approximate the water loading specific to an area, while knolls or high areas may tend to under-approximate the water loading.

The collection of rainfall and runoff is very important in a nonpoint source pollution study where mass balances of water are determined. For determining a water balance and solute loading, surface water instrumentation must be installed to measure surface runoff quantity and quality (Figure 24). Automated equipment is necessary for measuring rainfall intensity and amount to determine a water balance on a site. Rainfall intensity can be determined very easily using automated weather instruments and should be collected at least to the nearest minute (Figure 25).

Figure 24. Surface water runoff instrumentation for a vadose zone monitoring site.

Figure 25. Portable automated weather station.

Automated weather stations can be augmented with manual rain gages to backup the rainfall data in case weather stations malfunction. If the study site is located remotely from an official recording weather station, it becomes more important to incorporate weather stations into the project. The number of stations will depend upon the size and scope of the project.

In the South Dakota RCWP project, seven field sites and one research site were studied in a 15 square mile area. Only one weather station was instrumented in the area with a supplementary weighing rain gage added about half way through the project. The remaining information regarding rainfall depths was used from three nearby official weather stations. Data was triangulated at the monitoring sites from these three weather stations. Thunderstorm activity during the summer months created highly variable precipitation patterns. If the project were to be done again, there would be a recording rain gage installed at each site where intense studies were performed.

Freezing conditions

In the Upper Midwest, soil freezing over the winter months is very common and occurs at different depths, depending upon soil water content, soil texture, vegetation and residue, snow cover conditions, and average daily air temperature. For extensive soil freezing conditions, significant upward solute transport can take place during the freezing process, and downward during the thawing process (Galinato, 1987). The effects of surface freezing on soil temperature, moisture content, and nitrate distribution in laboratory soil columns with the bottom immersed in a solution at a constant head in presented in Figure 26. The movement of solutes within the vadose zone created by this phenomenon should be accounted for to prevent false interpretations of transport of solutes to a shallow aquifer. In Galinato's study, more upward solute movement during the freezing process was found to occur under wetter soil conditions. More upward water vapor (and less upward solute flow) movement was found to occur in drier soils. This phenomena has shown significant changes in vadose zone solute concentrations at different times of the year, and should be considered during the vadose monitoring planning stages.

The effect of soil freezing should be considered when installing monitoring instruments in the vadose zone. Considerations include: 1) Is the monitoring going to take place over the winter? and, 2) if so, will the instruments selected be able to measure selected parameters without damage to the sensors/instruments?

Impact of Surface Soil Management

Man's activities in managing the land can have significant impacts to the shallow ground water (Bischoff and Carlson, 1991). The type of crop, crop maturity, fertilizer practices and timing, tillage practices, and pesticide applications all affect the potential for movement of solutes and water to move through the vadose zone to the ground water (Lal and Stewart, 1994).

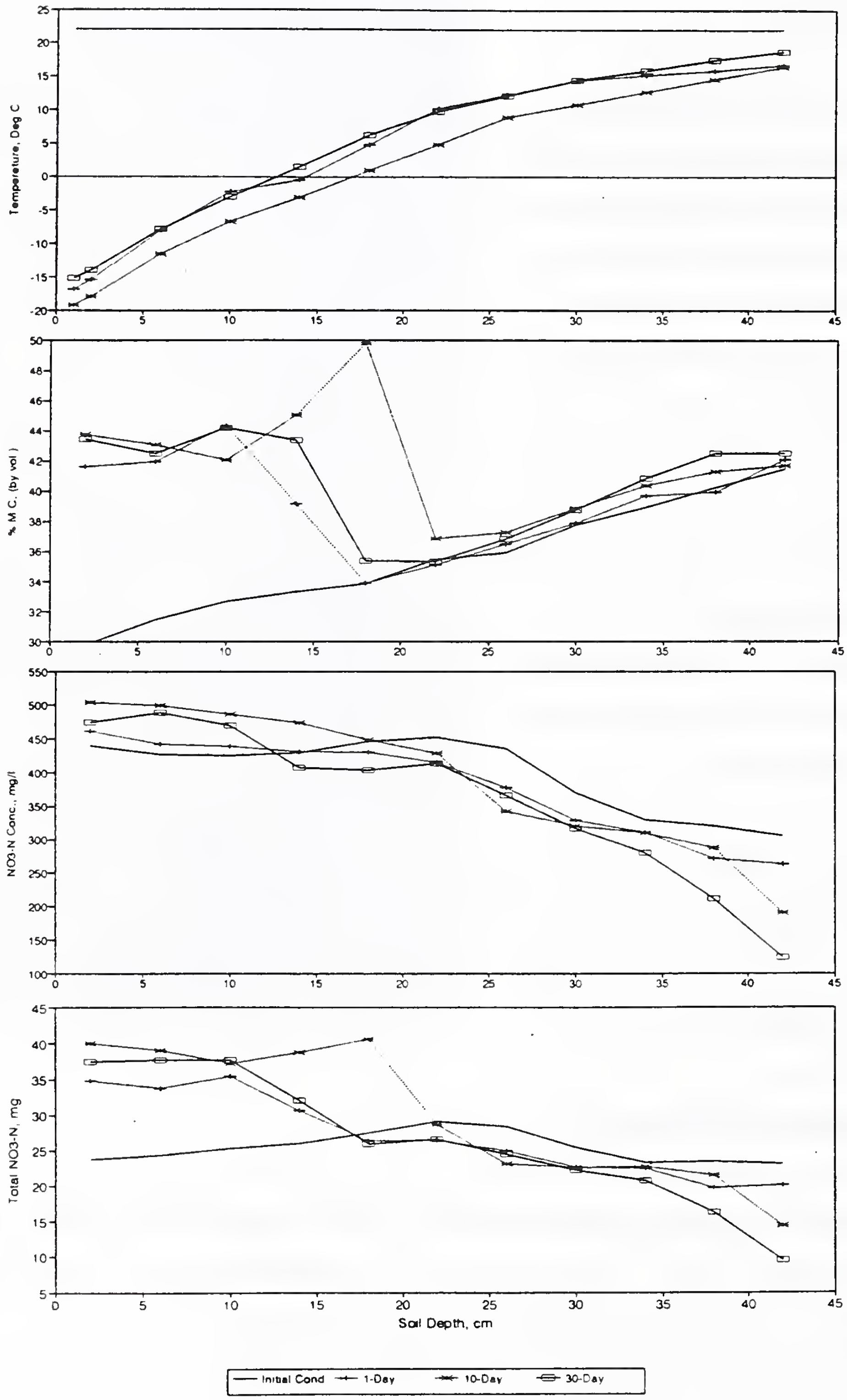

Figure 26. Effect of surface freezing on parameters in laboratory soil columns.

Crop

The type of crop grown affects the soil water content and time of year for soil water extraction by the plant (transpiration). Annual row crops which are planted in mid-spring have a much different pattern of water extraction from the soil than do perennial grasses, alfalfa, or clover. Not only is the growing season longer for perennials, but the nutrient and water uptake is more uniform throughout the growing season. Annual row crops may have higher total requirements for water and nutrients. Therefore, the need to provide water and nutrients over a narrower time frame is necessary for row crops to minimize plant stress.

Grasses and other perennials require lower peak nutrient and water requirements over longer periods of time; consequently, there is less need to provide supplemental water and nutrients. A greater percentage of the nutrient requirements are provided by the storage pool of organic nutrients mineralized in the soil profile. The understanding of these principles of crop growth, water and nutrient uptake, and timing of uptake will help plan for the frequency of sampling and necessary equipment to determine the water and solute content at various depths of the vadose zone.

Fertilizing

Timing, amount, and placement of fertilizer application for agricultural crops in addition to the type of fertilizer, is extremely important in minimizing transport of mobile nutrients to shallow aquifers. The fertilizer type, placement, and application method will determine the location of monitoring sites and parameters to test in the vadose zone (Bischoff, in progress; Clay, et al., 1992). In addition, the frequency of sampling in the vadose zone will be determined by the fertilizer management used on the site(s) to be studied. Split applications of mobile nutrients applied to fields may extend the vadose zone monitoring requirement compared to a one-time application of the same amount of nutrients applied.

Tillage

Tillage changes many physical, chemical, and biological/microbiological characteristics of the top 8-12 inches of soil. The intensity and frequency of tillage affects the rate of mineralization of organic matter and humus in the soil. Timing of the tillage will determine where and when dedicated instruments can be installed to monitor necessary soil characteristics.

If an automated/dedicated instrument system is used to monitor the vadose zone, coordination between project personnel and field operators regarding the placement of the instruments is essential to prevent instrument damage during agronomic operations.

Pesticides

If vadose zone monitoring includes the water quality parameters of pesticides, care should be taken to minimize the transport of adjacent off-site pesticides invading the field or plot. Surface water from adjacent fields was shown to carry pesticide residues during the South Dakota RCWP project monitoring (Goodman, et al., 1992). Recent information regarding the transport of pesticides through the atmosphere and deposited upon the land during rainfall has shown that this can be a mechanism of major pesticide transport, particularly during the periods of common applications throughout the Midwest.

The instrumentation sampling system should be protected from the potential contamination of pesticides washed from the atmosphere and those samples obtained from the vadose zone. Rainfall water quality may be analyzed separately for pesticides to eliminate potential background loadings of specific pesticides to the ground water by this alternative method of transport.

Impact of the Root Zone

The root zone varies in depth depending upon the type of crop, crop maturity, antecedent soil water conditions, water table position, and nutrients available in the soil. Roots in the soil are the **major** mechanism for removal of water and nutrients from the soil. The rate at which the plants remove the water and solutes may impact the type and extent of vadose zone monitoring used in studies. For example, alfalfa uses soil water (through transpiration) over a much longer period of time than oats, and the instantaneous rate of removal is higher.

In some parts of the Midwest and/or during drier climates, water from rainfall during the growing season may be less than that demanded by the crop. In this situation, roots will grow downward seeking additional water, thus lowering the water table. Certain crops have the ability to seek out water in this manner more than other crops. Vadose zone monitoring instruments dedicated to soil water monitoring should be chosen with this phenomenon in mind. Since the instruments are installed to monitor a given depth, a moving water table caused by either high or low water demand crops may require additional monitoring points. This is necessary to ensure some of the instruments are located in the vadose zone while some instruments may be monitoring saturated conditions.

The major mechanism for movement of mobile nutrients from the soil to the plant is by convective transport (movement in solution with soil water). The impact of the crop root zone on soil water in turn reflects that the major emphasis in vadose zone monitoring should be water movement. Because of the impacts of the root zone in shallow water table soils, monitoring the position of the water table during and after major recharge events is essential. This monitoring complements the monitoring of the unsaturated zone for determining mass transport of water and solutes to the water table.

VADOSE ZONE MONITORING EQUIPMENT AND PROCEDURES

Instrument Selection

The objective of in situ installation of vadose zone monitoring equipment is to describe the transport processes of soil water and solutes which may drain from the soil profile to the ground water. There are several instruments (or processes) available which have been designed for specific uses in vadose zone monitoring. The selection of a method of monitoring will lead to a particular instrument(s) for a given method. As an example, if spot checking a concentration of a specific solute is desired, soil sampling may be selected as the method of determining the concentration of the solute within the soil. This method would require someone to collect the sample at different time intervals, with the extraction of soil water from each soil sampling providing the concentration of the solute in question. If only this type of information is desired, the soil sampling mechanism would be the most cost effective method for achieving project objectives.

KEY LESSON LEARNED: Not all vadose zone monitoring instruments are suited for the determination of loading of contaminants to the ground water.

Methods to determine solute concentrations in the vadose zone are presented in Table 3. Methods for determining soil water pressure potential (soil water energy level) and soil water content are presented in Table 4.

Table 3. Methods for monitoring solute concentrations in the vadose zone.

Method	Advantages	Disadvantages	Relative Cost
Soil Samples	* Gives quick instantaneous results of concentrations of soil solutions;	* Destructive sampling technique is inherent; cannot determine mass loadings, only concentrations of matric water; requires many samples	Low
Suction Lysimeters	* Many variations of types; dedicated instruments can take many soil solution samples at one site over time;	* Can only be used in fairly moist soils; may extract matric water and not free drained water; for concentrations only;	Medium
Pan Lysimeters	*Useful in soils where an abrupt boundary in soil texture is encountered	*Difficult to install; high variability in data; many replications are needed	High
Tile Lines	*Gives excellent results of water and contaminant flux over large areas	*Water table may fall below tile lines; subsequent leaching to raise WT to tile lines will be lost	High
Shallow and Deep Wells	*Allows monitoring of WT position in fairly permeable soils; inferences about soil moisture above WT can be made	*Indirect measurements of soil moisture are only available; mass loadings of contaminants to the aquifer cannot be made	Medium
Large Block Lysimeters	*Loadings of contaminants to the aquifer are easily calculated	*Extremely expensive; disturbing of soil may influence results	Very High

Table 4. Methods for determining soil water pressure potential and soil water content.

Method	Advantages	Disadvantages	Relative Cost
Tensiometers	* Gives quick instantaneous results of soil energy level;	* hysteresis of wetting and drying soils; readout is to the nearest centibar	Low
Neutron Attenuation	*Gives accurate volumetric water content in all types of soils;	* Requires on-site manual readings of soil water content; Radioactive source; Integrates water content over a given volume	Moderate
Transiometers	*Determines energy level of water at a given point; can be used with automatic data loggers;	*Not widely available; tension is lost and instrument must be recharged in low moisture conditions	Moderate

A typical suction sampler/lysimeter with a porous cup interacting with soil water is illustrated in Figure 27. Figure 28 shows a tensiometer installed at a farmed field site. A probe used for soil sampling to determine concentrations of soil solutions is shown in Figure 29. The neutron attenuation probe inserted in an aluminum access tube is presented in Figure 30. A transiometer (top) prior to installation is shown adjacent to a tensiometer in Figure 31. A diagram of the transiometer construction is presented in Figure 32. Figure 33 illustrates a stainless steel pan used to collect percolating drainage water through shallow soils and a typical installation of a pan lysimeter. An example of a large block lysimeter is shown in Figure 34. Several other lysimeter installations are illustrated in Figures 35-37.

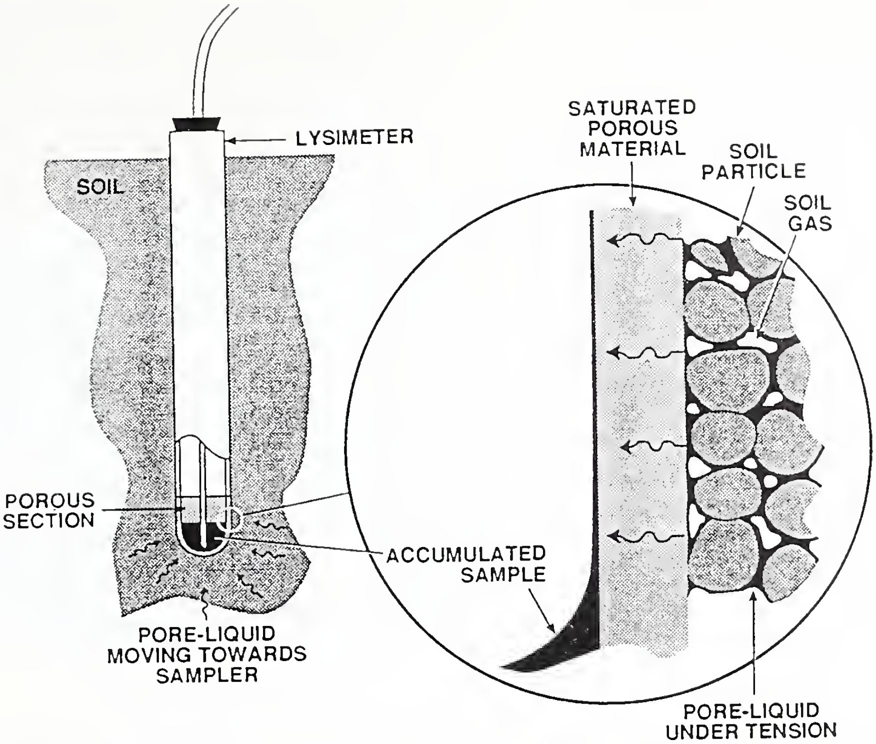

Figure 27. A typical suction sampler/lysimeter with a porous cup interacting with soil water (Nash and Leslie, 1991).

Figure 28. Tensiometer installed at a farmed field site.

Figure 29. Probe used for soil sampling.

Figure 30. Neutron attenuation probe in an access tube.

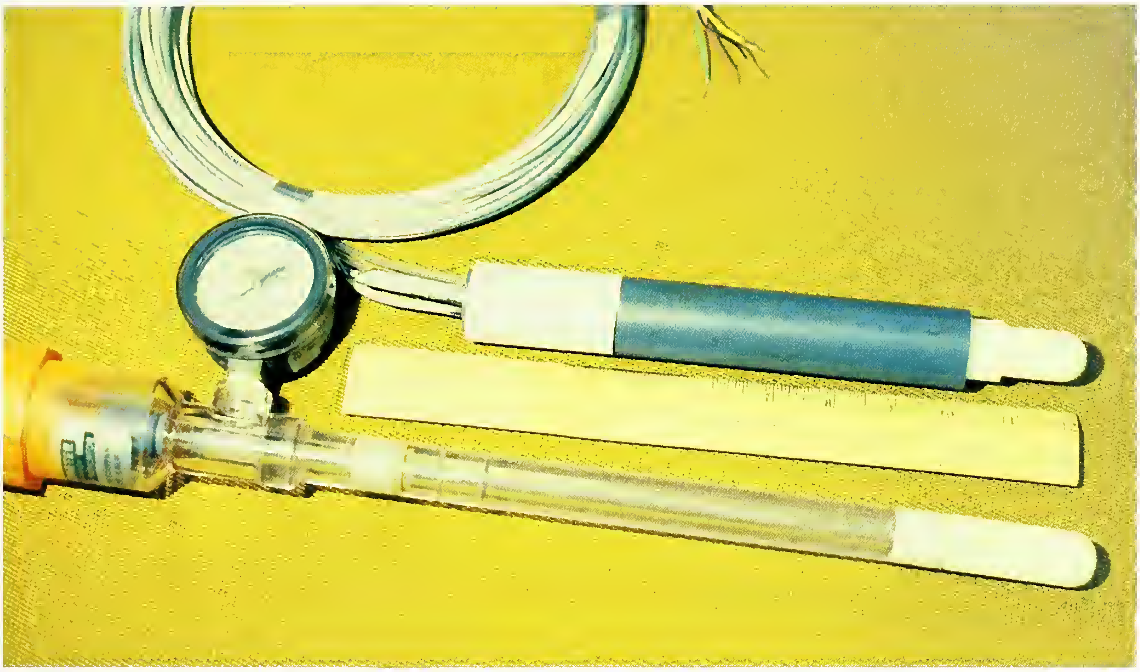

Figure 31. A transiometer (top) prior to installation adjacent to a tensiometer.

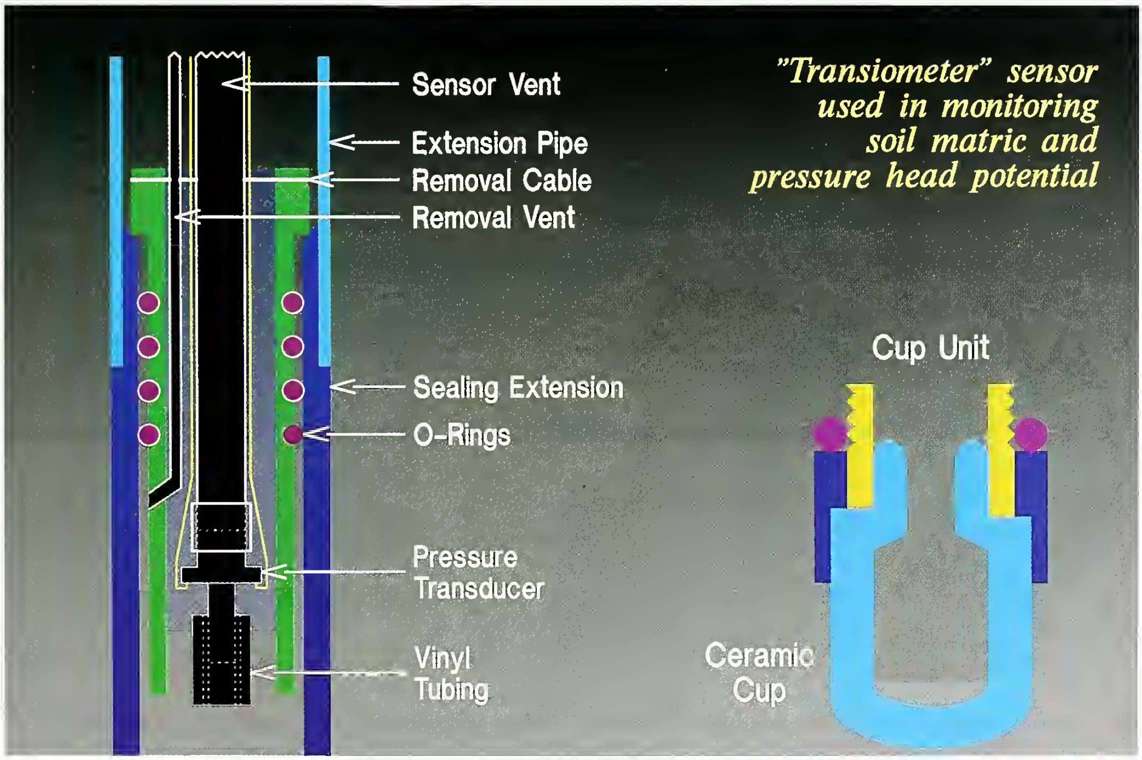

Figure 32. A diagram of the transiometer construction.

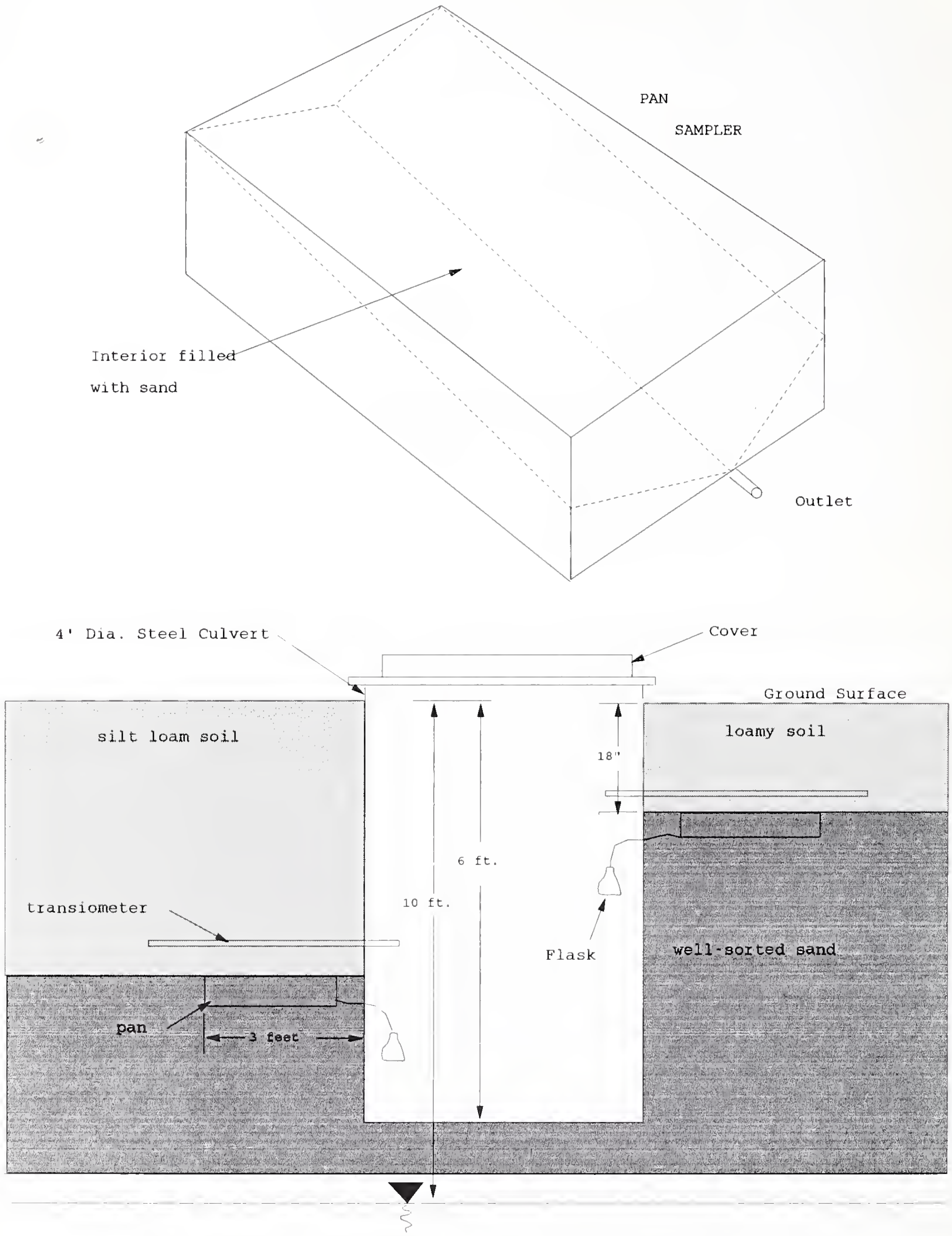

Figure 33. Stainless steel pan (top) and typical installation of a pan sampler (bottom).

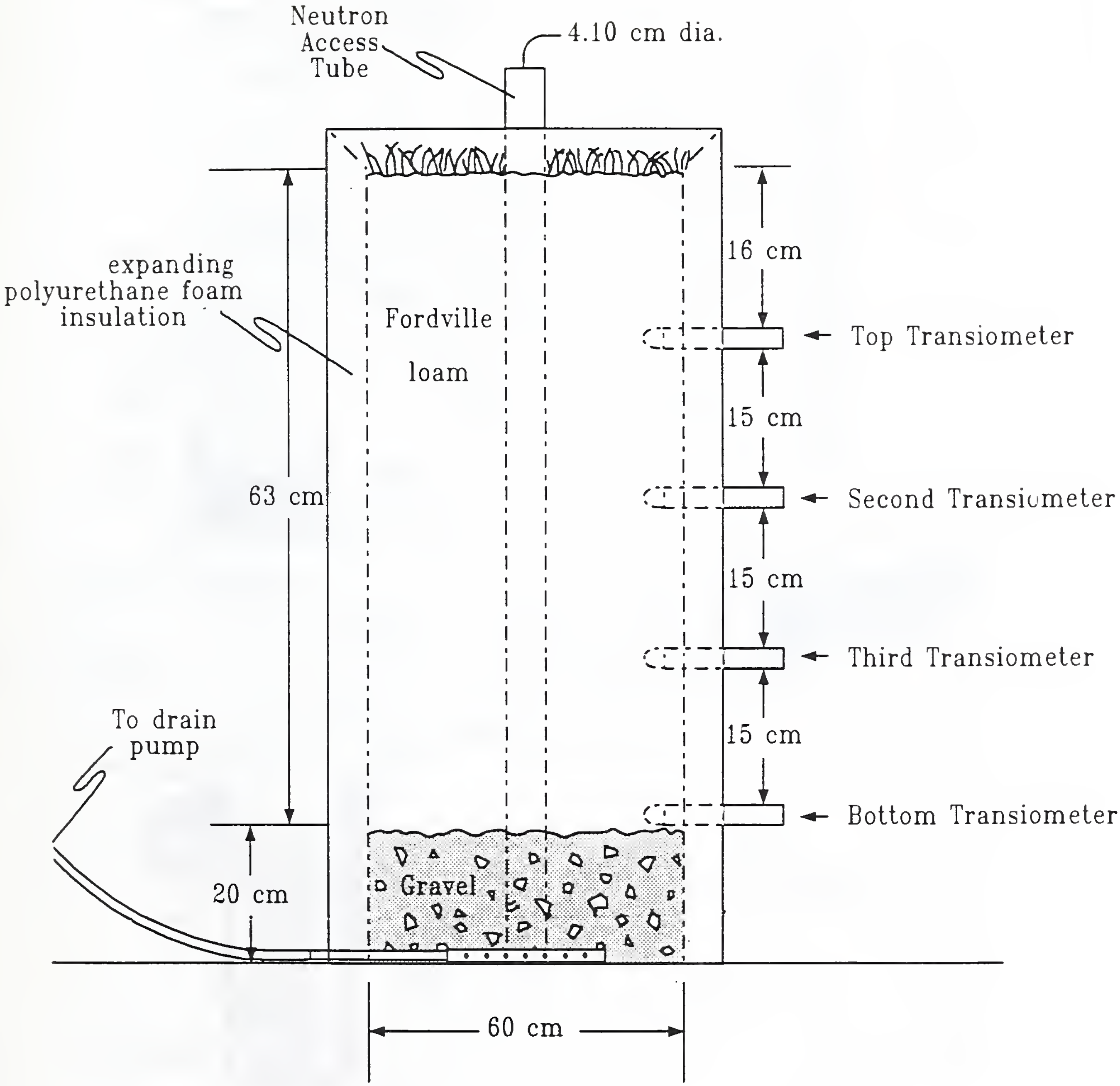

Figure 34. An example of a large block lysimeter.

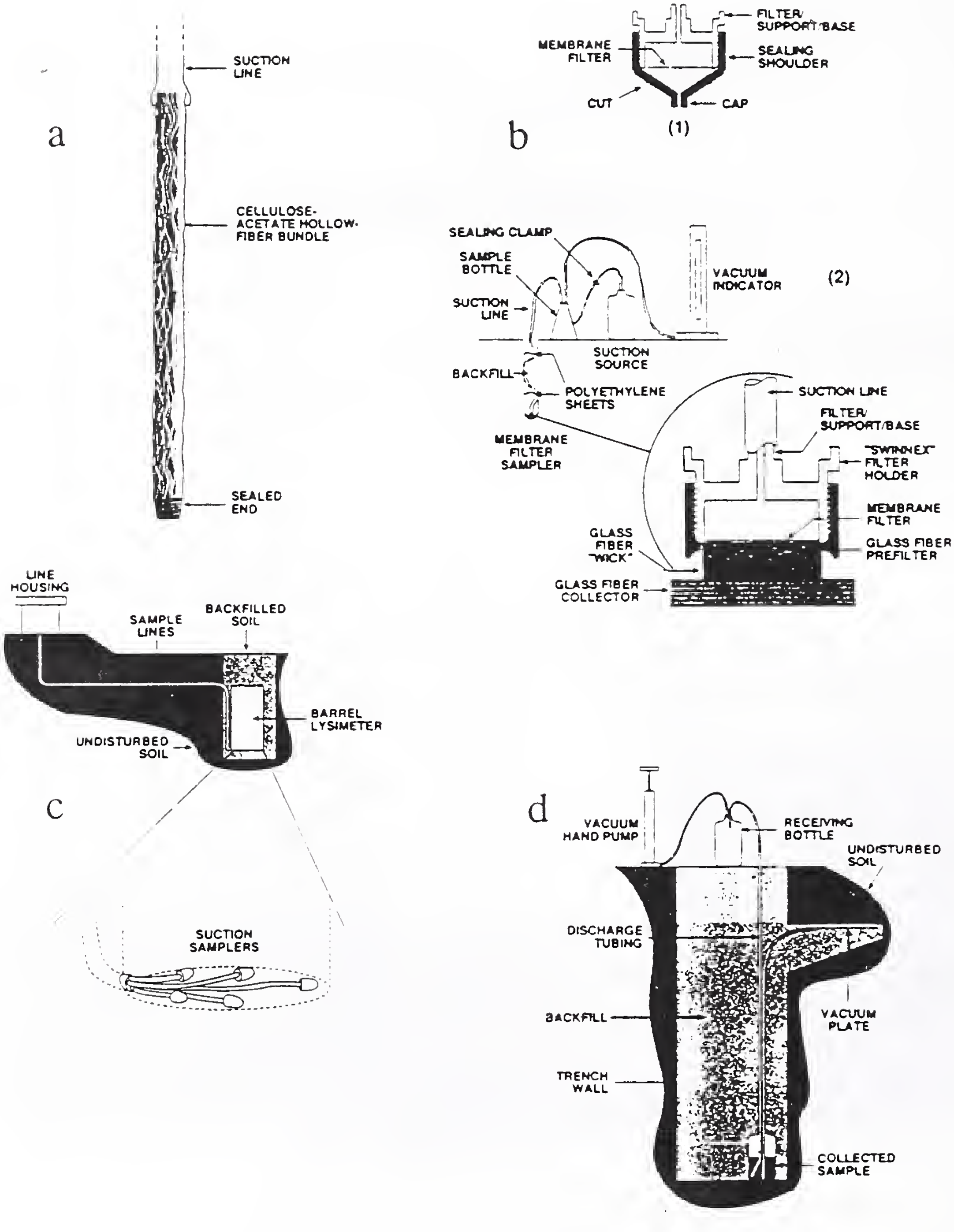

Figure 35. (a) Cellulose-acetate hollow-fiber sampler. (b) membrane filter sampler. (c) barrel lysimeter. (d) vacuum plate sampler installation (Nash and Leslie, 1991).

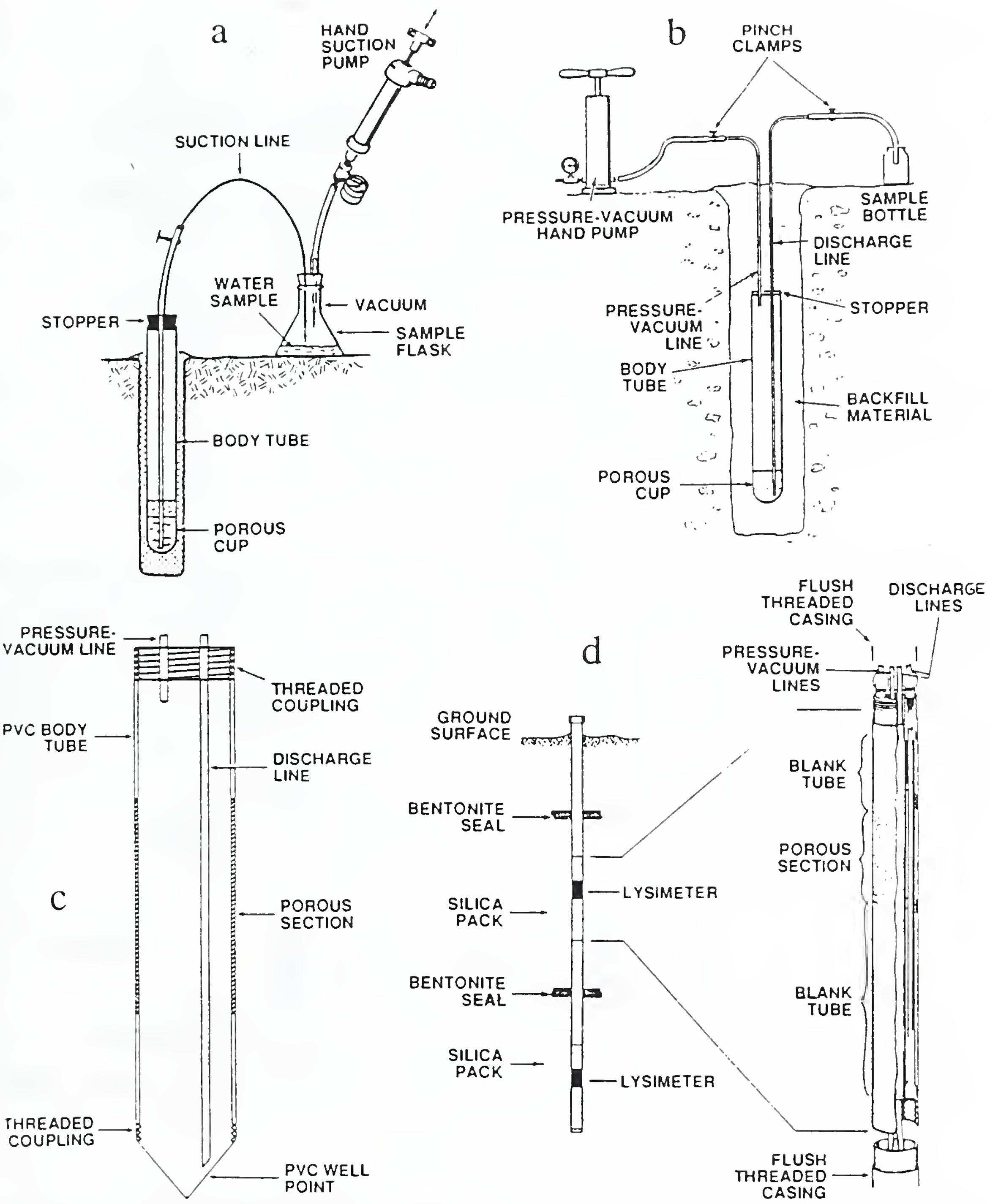

Figure 36. (a) Vacuum lysimeter. (b) pressure vacuum lysimeter. (c) tube pressure vacuum lysimeter. (d) casing lysimeter. (Nash and Leslie, 1991).

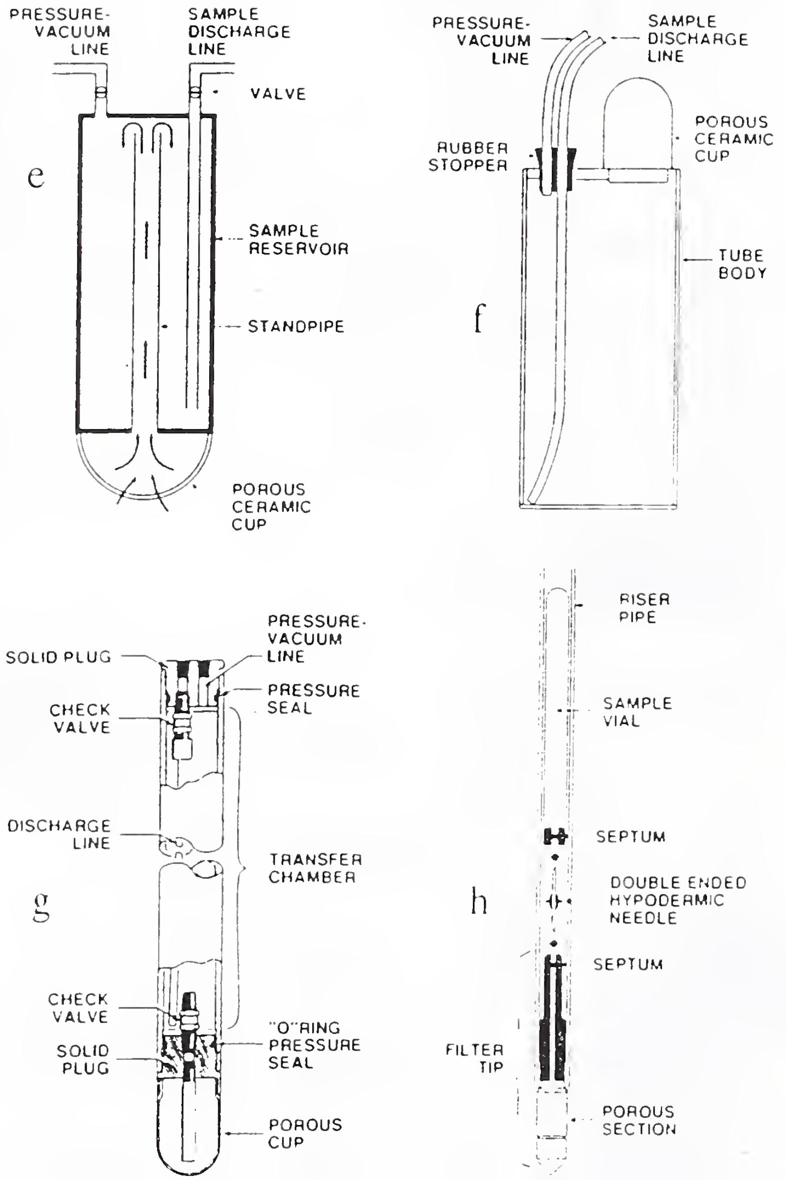

Figure 37. (e) Modified pressure-vacuum lysimeter. (f) Knoghton-Streblow type vacuum lysimeter. (g) high pressure-vacuum lysimeter. (h) filter tip sampler. (Nash and Leslie, 1991).

Nested shallow wells with screens installed to collect discreet samples throughout the entire saturated zone (Figure 3) may be used to help identify an **approximate** loading of water and solutes to the ground water. Nested wells are most useful if hourly water table positions are measured, and the amount and intensity of rainfall is measured to the nearest minute. Also, a method collection system (such as a skimmer pump mentioned in Clay, et al., 1994) which allows for the collection of water near the surface of the saturated zone after a rise in the saturated water level is detected, may be used to estimate recharge and loading of solutes. This method has promise for estimations but has not yet been field tested by many researchers. It is an indirect method of estimating drainage of water through the vadose zone. Impacts from off site water may affect the results from these instruments, and subsequently should be used in subsurface geology where lateral water influence is insignificant.

In homogeneous subsurface materials during periods when the vertical water gradient is minimal, estimates of the soil matric potential (negative soil pressure potential, ψ) can be made using shallow nested wells. An example would be: if the water table position were at 180 inches below the ground surface, and soil water movement was near equilibrium conditions, then the distance above the saturated zone should be nearly equal to ψ (i.e. soil matric potential at a point 50 inches above the water table in the above example would be approximately -50 inches).

New Technology

Some new technologies have been developed over the last few years which help to improve soil water measurements and soil water quality analysis. These instruments are:

Time Domain Reflectometry (TDR)

TDR is a unique automated method of determining soil water content by using a series of soil probe rods inserted either vertically or horizontally in the soil. This automated method was developed by University of Minnesota scientists and was perfected by Campbell Scientific Corporation[1], Logan, Utah. This instrument measures soil water content and discriminates between frozen or unfrozen soil water. This information, along with neutron attenuation, enables a determination of frozen and unfrozen soil water at specific depths. Neutron attenuation has not been developed for automation.

Capacitance-determined Soil Water Content

This instrument was developed by Troxler Electronics, Inc.[1] to measure soil water content in the same manner as neutron attenuation without the hazard associated with radioactive handling, storage, and disposal. It is a manually operated piece of equipment which has a probe lowered into an existing access tube installed vertically in the ground. The dissipation of the capacitance induced in the instrument is a function of the soil water content surrounding the tube.

[1]Mention of trade names is done for the reader's information. Mention of these product names does not imply endorsement by United State Department of Agriculture.

ON-SITE MONITORING DEVELOPMENT AND IMPLEMENTATION

The **type** of vadose zone monitoring to implement should be decided during the pre-project planning. These decisions are based on the characteristics of the vadose zone and the factors impacting these conditions discussed in the previous section. More details pertaining to vadose zone monitoring equipment and location will be decided during the investigation of the site and will depend on the vadose zone characteristics at each site. Decisions regarding the instruments

to use, depths to monitor, and number of sites to monitor may be modified during the implementation phase of the monitoring program.

The South Dakota RCWP project initially had both a controlled management field plot-scale site (the master site) and seven different field scale sites located within farmers' fields. The master site was a silty clay loam soil with glacial till subsoil monitored for both soil water content and matric potential at different depths. Nitrate concentrations from soil samples were collected once each year. The ground water table position and the ground water quality were not monitored. The field sites were monitored for soil water content and matric potential at different depths, the water table position, and ground water quality. The field sites had ground water samples evaluated for different forms of nitrogen, pesticides, and other chemical parameters.

After four years of data collection, a revision of the master site activities was needed to achieve the goal of determining best management practice impacts on ground water quality. These five things became evident: 1) the sensitivity of the tensiometers to changes in soil water matric potential was too coarse; 2) the tensiometer readings were not taken frequently enough to determine a water balance (once or twice weekly); 3) no water table position was monitored; 4) the recharge water was not being monitored for quality; and 5) the ground water quality data from the glacial till field sites showed higher concentrations of nitrates and more detections of pesticides than ground water samples from other geologic materials.

This monitoring revision was necessary because the existing instrumentation was not providing sufficient information to achieve the project objectives. Three main conclusions about the existing vadose zone monitoring were reached at the end of four years of master site and field site data collection: 1) it was postulated that soil water after a rainstorm was moving through the soil profile much quicker than originally anticipated; 2) a mass balance of water and solutes at the field sites could not be determined because water moving through the vadose zone to the

ground water was not being measured; and 3) a better instrumentation and sample collection system was needed to "see" the soil water moving through the soil profile, and mass loadings (how much mass of water and solutes were moving to the ground water under different best management practices) of solutes needed to be determined. In summary, project personnel were not able to measure the rate of water and solute movement through the soil and correlate this to the change in the ground water table position or impacts from best management practices.

A change in the method of data collection was proposed with instruments which were developed to collect soil matric potential and saturated water table levels automatically (tensiometers). A system that intercepted the soil water during and immediately after rainfall events was designed. The information from this system enabled project personnel to evaluate the impacts of alternative management practices on the movement of water and solutes through the soil profile to the ground water. Reevaluation and modification of the monitoring system helped to meet the objectives of determining best management practice impacts on vadose zone and ground water quality. Otherwise they would not have been fully achieved.

KEY LESSON LEARNED: For shallow unconfined ground water quality at the glacial till vadose zone monitoring site, there was a definite trend of seasonal variation of saturated zone nitrates. Nitrates generally increased in concentration as the growing season began and decreased over the winter.

Lessons Learned from RCWP

- **Measurement and collection of vadose zone water quality and quantity is a complex and expensive monitoring endeavor.**

- **Movement of soil water through the vadose zone in preferential flow can be extremely rapid under wet conditions compared to traditional plug flow permeability theory. For a moderate rainfall intensity (1.8 in/hr), a unique tracer dye was found to show that concentrations simulate a runoff hydrograph at depths to 6 feet within 2 hours of application on fine-textured glacial till soils and subsoils.**

- **If soil drainage water quality and quantity are to be measured in situ, automated systems to measure and collect soil water should be installed to ensure realistic results.**

- **Transiometers are effective instruments to monitor soil water pressure potential (SPP) under moist or wet soil conditions.**

- **Rainfall events of higher intensity and amounts under wetter soil conditions are conditions which mainly tend to recharge the ground water.**

- **Many of the vadose zone instruments for measurement and collections of soil water are designed for specific soils and subsurface geologies. What may work for glacial till soils may not be desirable for outwash soils.**

DATA EVALUATION

To calculate the loadings of agricultural chemicals to the ground water, some measure of the depth of new water moving to the ground water system must be made. If concentrations of specific agricultural chemicals in question are known during the recharge events, then loadings of these chemicals to the ground water system can be obtained. Clearly, it is the hydrologic component of the agricultural chemical transport models that is the least understood, and is the

most important to understand before any accurate assessment of the chemical transport can be made. In determining this water flux for the system used at the South Dakota RCWP project, the change in water table position (increase) for a given event multiplied by the drainable porosity of the material directly above the water table gives a good estimate of the water loading to the water table.

Water Flux

Water and solute (i.e. NO3-N) flux can be calculated from known drainable porosities, water table rise, and solute concentrations from the various depths of unsaturated soil. The water flux is determined by the following:

$$D.\ P.\ \ x\ \ WTR = q_w \tag{1}$$

where D.P. = drainable porosity (of the material of the water table rise), dimensionless,

WTR = water table rise (length, L) for a given leaching event (time, T), and

q_w = soil water flux, (length, L per unit area, L^2 per unit time, T) for the length of the given event

Calculating Solute Flux

Calculation of the solute flux is the concentration of the solute in the water sample extracted during the leaching event multiplied by the depth of water flow:

$$q_s = q_w \frac{(c_o)}{4.415} \tag{2}$$

where q_s = solute flux, pounds per acre per event

where q_s = solute flux, pounds per acre per event

c_0 = concentration of the solute for the event, mg/liter, and

4.415 = conversion factor

An assumption in this methodology is that the capillary fringe of the water table (approximately 2 feet) has a substantial portion of the soil matrix nearly saturated. The pores which are not saturated are those which are filled rapidly due to macropore water movement over the area. Therefore, any decline in the water table after a leaching event has occurred is due mainly to crop uptake and the slow upward capillary movement of water to create the new fringe. Thus, if a leaching event raises the water table within the height of the capillary fringe, the immediate response of the water table a few hours after the peak would be the best reading to record to represent the change in the water table position (Figure 38). Obviously, as the hydraulic conductivity (and drainable porosity) of a given material near the water table increases, the response of the water table to the infiltration event would increase, and the concerns relative to the time factor of filling matrix pores would decrease.

This procedure was used on the Oakwood Lakes-Poinsett RCWP project. The results showed that although the average seasonal nitrate concentrations were higher for moldboard plow tillage compared to no-till, the water flow was higher for the no-till contributing to higher ground water loadings for the no-till treatment.

The reader is referred to Goodman, et al. (1991) and Bjorneborg (1989) for a more detailed discussion of the vadose zone monitoring in the South Dakota RCWP project. This includes equipment used, installation techniques developed, and the results produced from the project. Other suggested references for vadose monitoring include: Logan et al., (1987), Everett and Cullen (1995), Hemond and Fechner (1994), Luckner et al., (1991), Honeycutt and Schabcker (1994), and Stephens (1995).

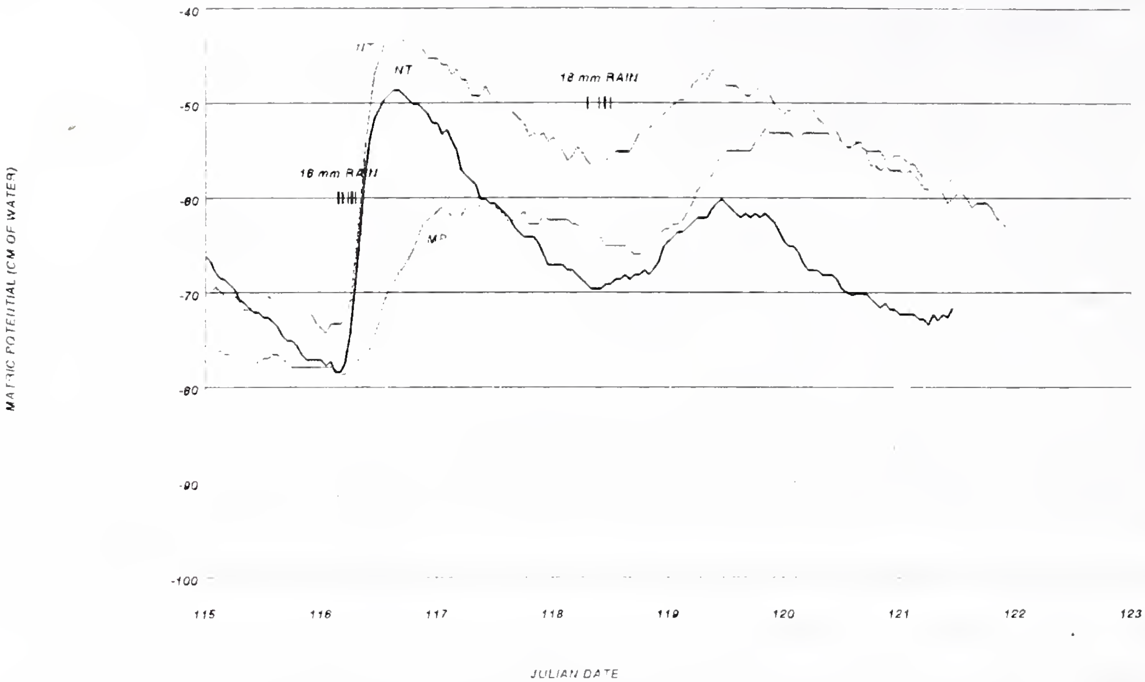

Figure 38. Response of soil matric potential to 2 rainfall events on 2 no-till and 2 moldboard plow tillage treatments as read by transiometers at the 2 foot depth.

VADOSE ZONE MONITORING SUMMARY

To summarize the steps involved in designing a vadose zone monitoring system, use the following guidelines:

Pre-monitoring Planning & Design

1) Determine <u>which zone(s)</u> will be monitored (vadose, saturated, root zone, all)
2) Determine the <u>extent of monitoring</u> (mass loadings of water and solutes, or concentrations of solutes only)
3) Approximate the <u>number of sites</u> to derive unsaturated zone data
4) Determine the <u>type of monitoring</u> to use (automated, grab, or combinations)
5) Determine the <u>scale of vadose zone monitoring</u> (field, plot, lab, etc)

On-site Monitoring Development and Implementation

1) Determine what <u>depths and increments</u> to sample/monitor
2) Determine site specific <u>soil and subsurface geologic characteristics</u>
3) Determine the <u>agronomic management practices</u> to monitor
4) Determine the <u>parameters to quantify for evaluation</u>
5) Determine the <u>frequency</u> of sampling/monitoring (event-based, rhythmic, grab)
6) Determine the <u>climatic parameters</u> that need to be monitored at each site/station
7) Select the <u>type of instruments</u> to use to sample/monitor the vadose zone

VADOSE ZONE GLOSSARY

(The following list of glossary terms is compiled from several sources including the following: Driscoll, F.G., Groundwater and Wells, 1986; Practical Handbook of Ground-Water Monitoring, edited by Nielsen, D.M., 1991; Jury, W.A., Gardner, W.R., and Gardner, W.H., Soil Physics, 5th Edition, 1991)

biomass - the living system including animals, plants, bacteria, insects, fungi, etc. of a given area

conservation tillage - any tillage and planting system in which at least 30% of the soil surface is covered by plant residue after planting

detection limit - the lowest concentration of a chemical that can be reliably reported to be different than zero

downgradient - in the direction of decreasing hydrostatic head

drainable porosity - the ratio of the volume of water that will be released per unit volume of soil by lowing the water table

evapotranspiration - the sum of evaporation plus transpiration

glacial till - a term for unconsolidated, unstratified, and unsorted glacial drift deposited directly by and underneath a glacier without subsequent reworking by meltwater. It consists of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.

hydraulic conductivity - a coefficient of proportionality that describes the rate at which a fluid can move through a permeable medium. It is a function of both the medium and of the fluid flowing through it.

leach - to wash or drain by percolation

lysimeter - a vadose zone sampling device used to collect soil pore water via suction in the unsaturated or saturated zone

macropore - a soil pore larger than a root tip diameter (0.2 mm diameter and larger)

macroporosity - the volume of pore space in soils made up of pores with an equivalant circular diameter of 0.2 mm and larger

matric potential - the energy per unit volume of water required to transfer an infinitesimal

quantity of water from a reference pool of soil water at the elevation of the soil to the point of interest in the soil at reference air pressure. It is the negative portion of the soil pressure potential.

no-till - an agricultural management practice where the soil is left undisturbed from harvest to planting

outwash - stratified sand and gravel removed or washed out from a glacier by meltwater streams and deposited in front of or beyond the end moraine or the margin of an active glacier

soil pressure potential - the negative (matric or unsaturated) or the hydrostatic (pressure) potential of water in soils, a term which covers either case of potential at a point in the soil

tensiometer - a device used to measure the in situ soil water pressure potential in soils at limited depths below ground surface

transiometer - an electronic device used to measure the in situ soil water pressure potential at any given depth below ground surface

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